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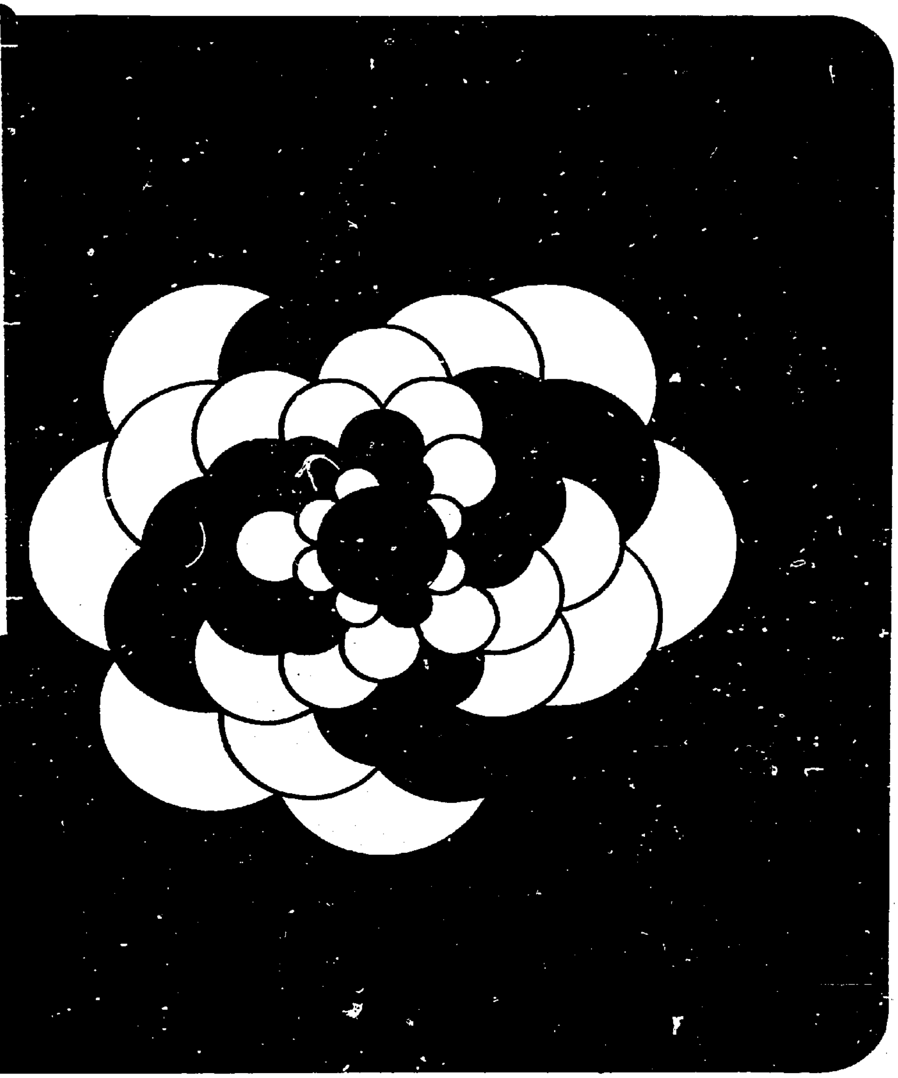
ABSTRACT

This booklet is part of the "Understanding the Atom Series," though it is a later edition and not included in the original set of 51 booklets. A basic survey of the principles of nuclear energy and most important applications are provided. These major topics are examined: matter has molecules and atoms, the atom has electrons, the nucleus, visualizing the atom, the chemical elements, energy comparisons, nuclear radiations and their penetration of materials, nuclear energy released, nuclear reactors, and service to man. Numerous photographs and diagrams are utilized. (PR)

atomic energy basics



U.S. ATOMIC ENERGY COMMISSION Division of Technical Information

This booklet provides a basic survey of the principles and the most important applications of nuclear energy. It is intended for those who are not professionally involved in the field but who need a general understanding of one of the forces which is reshaping our world. References to other works are inserted throughout the text for those who need more detail.

Edward J. Brunenkant

Edward J. Brunenkant, Director
Division of Technical Information

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atomic energy basics

(continued)

United States Atomic Energy Commission
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MATTER HAS MOLECULES AND ATOMS*

All matter—everything we can see or touch or taste or smell—is built of one or more kinds of molecules. There are innumerable kinds of molecules. Molecules, in turn, are built of different atoms. All molecules can be separated into their constituent atoms by different kinds of energy, for instance by electrical, mechanical, chemical, heat, or nuclear energy.

But any atom—such as an iron, oxygen, hydrogen, aluminum, or magnesium atom—can be separated into its parts only by nuclear energy, as will be described later. The other kinds of energy are not able to divide an atom. Regardless of how many times a piece of iron were halved, assuming no limit, the smallest possible division would be an atom of iron. Likewise, a lump of charcoal, thoroughly pulverized, would never yield a particle smaller than an atom of carbon.

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*For more information see *Our Atomic World*, an Understanding the Atom booklet.

At present, 105 different kinds of atoms have been identified, 92 in nature and 13 man-made. These are called *elements*, simple substances that either singly or in combination constitute all matter.*

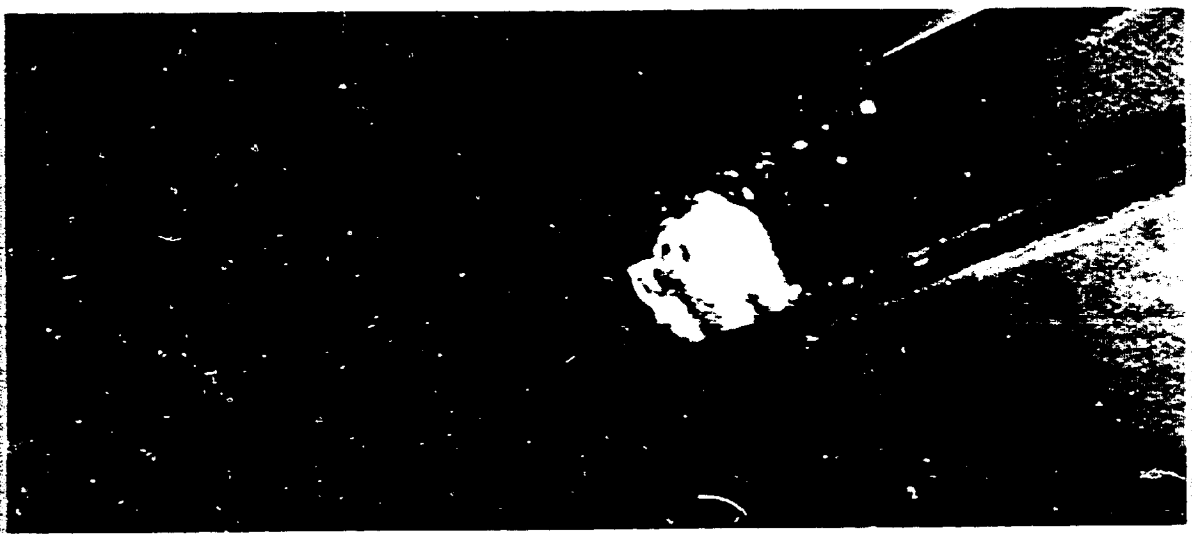
Every material substance—wood, steel, bone, cloth, paper, etc.,—is made of various combinations of these elements. The combinations of elements in the structures of these substances are analogous to the more than 600,000 words in the dictionary, each made of different combinations of the 26 letters of the alphabet.

A molecule that contains two or more different kinds of atoms is a *compound*, a distinct substance formed by chemical union between two or more elements that combine in definite proportion by weight. Two examples of compounds are water and iron oxide. Water contains two hydrogen atoms and one oxygen atom and has the chemical symbol, H_2O. Iron oxide contains either one iron and two oxygen atoms, FeO_2, or two iron and three oxygen atoms, Fe_2O_3. Ordinary table salt is another simple molecule which has two kinds of atoms linked together to form the molecule, NaCl. Some molecules contain only one kind of element; for instance hydrogen has two hydrogen atoms per molecule.

Strangely enough, molecules are apt to be physically unlike their atoms. A molecule of sugar is a compound of carbon (a solid), and

The scientific team responsible for the discovery of element 103, lawrencium. Left to right: Torbjorn Sikkeland, Albert Ghiorso, Almon E. Larsh, and Robert M. Latimer.

*For more information see *Discovery and Synthesis of the Chemical Elements*, Lawrence Radiation Laboratory, University of California, Berkeley, 19 pp., available from USAEC, P. O. Box 62, Oak Ridge, Tennessee 37830.



The first pure californium, element 98, magnified about 70 times, which was isolated in 1960. The crystals are lodged in a capillary tube.

hydrogen and oxygen (two gases). Ordinary table salt is a compound of sodium (a metal which burns rapidly in air) and chlorine (a toxic gas). Plain water, the most plentiful compound on earth, is a combination of hydrogen (a gas which burns) and oxygen (a gas which supports burning).

THE THREE STATES OF MATTER

Any portion of matter can usually exist in the solid, liquid, or gaseous *states*—that is, conditions or modes of being. All molecules of the same chemical substance are identical, regardless of the state in which they occur. They have the same number and kinds of atoms and the same structural arrangement. Water, for example, always has the same two gaseous constituents per molecule, whether frozen solid, a liquid, or a vapor.

TABLE OF THE ELEMENTS

1 Hydrogen H 1.008								
3 Lithium Li 6.94	4 Beryllium Be 9.01							
11 Sodium Na 22.9	12 Magnesium Mg 24.3							
19 Potassium K 39.1	20 Calcium Ca 40.1	21 Scandium Sc 44.9	22 Titanium Ti 47.9	23 Vanadium V 50.9	24 Chromium Cr 51.9	25 Maganese Mn 54.9	26 Iron Fe 55.8	27 Cobalt Co 58.9
37 Rubidium Rb 85.4	38 Strontium Sr 87.6	39 Yttrium Y 88.9	40 Zirconium Zr 91.2	41 Columbium Cb 92.9	42 Molybdenum Mo 95.9	43 Technetium Tc (99)	44 Ruthenium Ru 101.1	45 Rhodium Rh 102.9
55 Cesium Cs 132.9	56 Barium Ba 137.3	57 Lanthanum La 138.9	72 Hafnium Hf 178.4	73 Tantalum Ta 180.9	74 Tungsten W 183.6	75 Rhenium Re 186.2	76 Osmium Os 190.2	77 Iridium Ir 192.2
87 Francium Fr (223)	88 Radium Ra 226	89 Actinium Ac 227	104	105 Hahnium Ha 260				

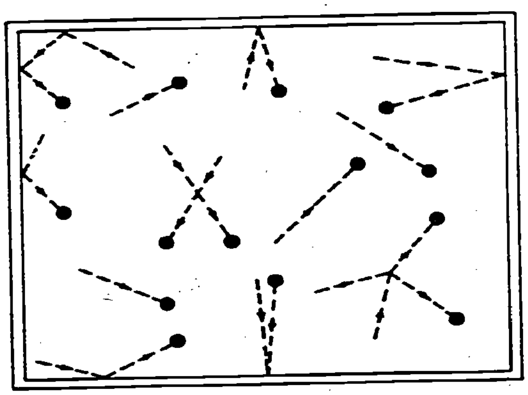
Atomic number—	1
	Hydrogen
Symbol—	H
Atomic weight—	1.008

Lanthanum Series	58 Cerium Ce 140.1	59 Praseody-mium Pr 140.9	60 Neodymium Nd 144.2	61 Promethium Pm (145)	62 Samarium Sm 150.3
Actinium Series	90 Thorium Th 232	91 Protactinium Pa 231	92 Uranium U 238	93 Neptunium Np (237)	94 Plutonium Pu (242)

								2 Helium He 4.003
			5 Boron B 10.8	6 Carbon C 12.0	7 Nitrogen N 14.0	8 Oxygen O 16.0	9 Fluorine F 18.9	10 Neon Ne 20.1
			13 Aluminum Al 26.9	14 Silicon Si 28.0	15 Phosphorus P 30.9	16 Sulfur S 32.0	17 Chlorine Cl 35.4	18 Argon A 39.9
28 Nickel Ni 58.7	29 Copper Cu 63.5	30 Zinc Zn 65.3	31 Gallium Ga 69.7	32 Germanium Ge 72.5	33 Arsenic As 74.9	34 Selenium Se 78.9	35 Bromine Br 79.9	36 Krypton Kr 83.8
46 Palladium Pd 106.4	47 Silver Ag 107.8	48 Cadmium Cd 112.4	49 Indium In 114.8	50 Tin Sn 118.6	51 Antimony Sb 121.7	52 Tellurium Te 127.6	53 Iodine I 126.9	54 Xenon Xe 131.3
78 Platinum Pt 195.1	79 Gold Au 196.9	80 Mercury Hg 200.5	81 Thallium Tl 204.3	82 Lead Pb 207.1	33 Bismuth Bi 208.9	84 Polonium Po 210	85 Astatine At (211)	86 Radon Rn 222

63 Europium Eu 151.9	64 Gadolinium Gd 157.2	65 Terbium Tb 158.9	66 Dysprosium Dy 162.5	67 Holmium Ho 164.9	68 Erbium Er 167.2	69 Thulium Tm 168.9	70 Ytterbium Yb 173.0	71 Lutetium Lu 174.9
95 Americium Am (243)	96 Curium Cm (245)	97 Berkelium Bk (249)	98 Californium Cf (249)	99 Einsteinium Es (254)	100 Fermium Fm (252)	101 Medelevium Md (256)	102 Nobelium No (253)	103 Lawrencium Lw (257)

The molecules, even of a solid, are not packed together tightly but have spaces between them, and constantly move. Gases are less dense than liquids, which are less dense than solids. On the other hand, molecules to some extent permeate all space, even the best vacuums man can create, and outer-space. The forces of attraction between the molecules in solids, and to a lesser extent in liquids, restrict their movement and hold them near fixed positions. In gases the speed of travel is tremendous because molecules are far enough apart to be free from this mutual attraction. In a closed vessel they rebound against the container vessel walls and each other, constantly changing speeds and directions. The effect of their combined impacts against the vessel walls is felt as vessel pressure. In liquids the speed is less, while in solids the movement may best be described as a slight vibration. Every molecule moves. There is internal movement in a piece of wood, a chair, or a bar of metal.



The push of gas molecules against the container sides is the pressure of the gas.

Consider how liquid molecules behave when they are heated in a closed container, for example in a pressure cooker on a kitchen stove. Molecular motion becomes more vigorous, and the temperature rises. As the temperature rises, some of the faster-moving molecules overcome the cohesive forces holding them together, and they break away from the surface to enter the gaseous state—that is, the liquid vaporizes. In the gaseous state these molecules no longer vibrate near fixed positions, but separate from each other and move in straight lines at speeds that increase with gas temperature. Their directions and speeds of travel change constantly from their frequent collisions with each other and with the vessel walls. Their random impacts against the vessel walls account for the pressure the heated gas exerts, as read on the pressure gage.

CHEMICAL REACTIONS BETWEEN MOLECULES

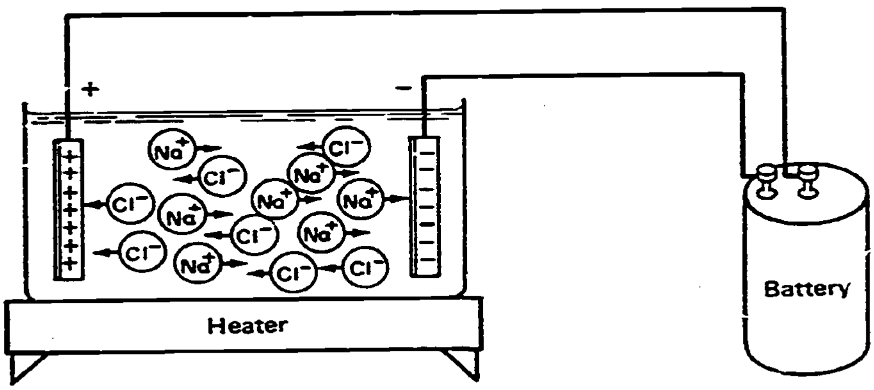
Molecules of different kinds may react with one another chemically to produce other different molecules. Some reactions proceed spontaneously at ordinary room temperatures when the elements are brought together, like phosphorous which burns when opened to the oxygen in the air, or like an iron bar exposed to the weather which slowly rusts away to iron oxide. Other reactants like gasoline and oxygen require a stimulus such as a spark to initiate their reactions, and then they proceed almost instantaneously. An automobile travels because a continual series of gasoline vapor and oxygen explosions push the pistons in the motor up and down to turn the crankshaft and propel the vehicle. On the other hand, oxygen in the air reacts more slowly with some substances like wood that burns, or like the iron bar that rusts.

MOLECULES SEPARATE INTO ATOMS

Many industrial processes today separate molecules into their atoms, or they build up valuable molecules from other more plentiful ones. Such processes, in the fields of chemical engineering and metallurgy, represent a big portion of today's technology. These processes depend upon being able to separate, change, modify, and tailor-make molecular structure to order as dictated by the consumer's demand and the process designer's technical skill. A number of such processes are based upon the two different molecular separation steps of *electrolysis* and *chemical reduction,* where the energy to separate molecules comes, respectively, from electrical and chemical energy.

Electricity passing through water will separate water molecules into their hydrogen and oxygen atoms. A science teacher sometimes introduces science to his class by making this separation in a simple battery-operated electrolytic cell. On some submarines the electrolysis of water furnishes oxygen for replenishing the depleted oxygen content of the vessel's supply of air for breathing. Similarly, electrolysis separates other molecules into their atoms. Most of the world's

aluminum and magnesium metals come from the electrolytic reduction of their ores. The typical metal and oxygen atoms are electrolytically separated in the same manner as the oxygen and hydrogen atoms of water.



Electrolysis of sodium chloride

The molecules of metals were first separated into their atoms by *chemical reduction.* Man probably first smelted a bronze ingot from copper and tin ores that by chance had been roasted in a hot enough charcoal fire. The ore reacts chemically with carbon monoxide, a product of most fires, to chemically reduce the ore to metal.

THE ATOM'S STRUCTURE POSTULATED

The modern miracle of the atom's peaceful progress is the climax of a long and continuous search for knowledge, and typically illustrates how scientific knowledge often starts with a postulate. Though bricks are thought of as the fundamental unit in brick buildings, the bricks themselves are sand and clay. By a similar analogy, scientists postulated that atoms have a construction of their own, distinct from the molecules they compose. This was finally proven after the idea had been held for centuries as a tradition.

Chronology

1800	Dalton firmly establishes atomic theory of matter.
1890–1900	Thomson's experiments with cathode rays prove the existence of electrons. Atoms are found to contain negative electrons and positive electric charge. Becquerel discovers unstable (radioactive) atoms.
1905	Einstein postulates the equivalence of mass and energy.
1911	Rutherford recognizes nucleus.
1919	Rutherford achieves transmutation of one stable chemical element (nitrogen) into another (oxygen).
1920–1925	Improved mass spectrographs show that changes in mass per nuclear particle accompanying transmutation account for energy released by nucleus.
1932	Chadwick identifies neutrons.
1939	Discovery of uranium fission by German scientists.
1940	Discovery of neptunium by Edwin M. McMillan and Philip H. Abelson and of plutonium by Glenn T. Seaborg and associates at the University of California.
1942	Achievement of first self-sustaining nuclear reaction, University of Chicago.
1945	First successful test of an atomic device, near Alamagordo, New Mexico, followed by the dropping of atomic bombs on Hiroshima and Nagasaki.
1946	U. S. Atomic Energy Commission established by Act of Congress. First shipment of radioisotopes from Oak Ridge goes to hospital in St. Louis, Missouri.
1959	First nuclear-powered merchant ship, the *Savannah*, launched at Camden, New Jersey. Commissioning of first nuclear-powered Polaris missile-launching submarine *George Washington*.
1961	A radioisotope-powered electric power generator placed in orbit, the first use of nuclear power in space.
1962	Nuclear power plant in the Antarctic becomes operational.
1963	President Kennedy ratified the Limited Test Ban Treaty for the United States on October 7.
1964	President Johnson signed law permitting private ownership of certain nuclear materials.

Scientists were amazed as anyone at where their postulate led them. They found the atom, building block of all matter, to be a collection mainly of three electrical particles—negatively charged electrons, positively charged protons, and neutral neutrons. The parts were indeed as unlike the whole as the atom itself was unlike its molecular composite.

More astounding, the countless applications today of atomic energy depend basically upon a portion of the atom's mass being converted into energy. The equivalence of mass and energy was first broached as a concept only early in this century by Albert Einstein, brilliant

Albert Einstein in 1905

mathematician-physicist. He described the atom's strange and wonderful structure with some Biblical language from the book of Hebrews, "... things which are seen were not made of things which do appear."

The search for information about the atom started more than 2000 years ago in ancient Greece. Democritus, a philosopher, reasoned that everything in the world consists of tiny pieces he called atoms which were simply envisioned as solid balls. This erroneous concept of atomic structure persisted until the end of the last century.

*THE ATOM HAS ELECTRONS**

The fact that atoms link together to form molecules indicated that the atom is not simply constructed. Atoms bond together with great tenacity in many cases and require energy to separate them. What are these bonds? The answer came from a search into the basics of electricity, from which the chemical bond between atoms was discovered to be of an *electron* nature.

ELECTRONS IN ORDINARY MATERIALS

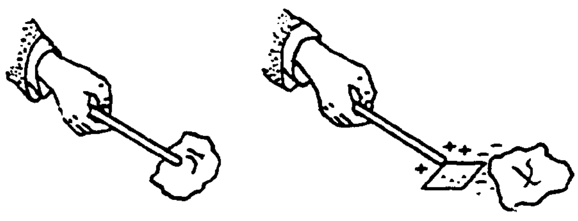
An amber rod that has been rubbed with a piece of cloth will attract and pick up bits of straw or paper, but the same rod will repel pith balls suspended from threads. This experiment, of novel interest for centuries, demonstrates the basic electrical principle that *like*

*For more information see *Our Atomic World*, an Understanding the Atom booklet, and *Basic Nuclear Physics*, Texas Atomic Energy Research Foundation, Fort Worth, Texas, Box 970, 76101, 1963, 43 pp.

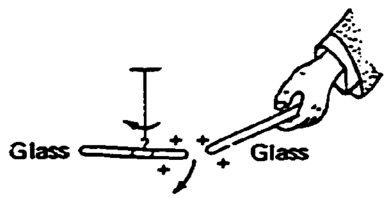
charges attract and unlike charges repel. This shows, too, that ordinary materials contain electrons. The unknown energy was named *electricity* after the Greek word *elektron,* for amber, some time in the late 16th Century. The amber has a surplus of free electrons, imparted to it from the cloth by the rubbing action, and is therefore negatively charged. It will repel other negatively charged bodies, and will attract positively charged bodies, which lack enough electrons to be neutral. This is *static electricity,* produced by static discharge, in this case from cloth to amber. Static electrons normally exert their force without moving from the place where they collect.

These same electrons, however, can *flow* through a metal conductor like a wire, or even across an airgap. They do this when they light an incandescent light bulb filament, or when they jump in a spark from finger tips to a car door handle. These electrons accumulate on a person's body from having rubbed across the car's plastic seat covers, for the same reason that electrons accumulate on the amber rod rubbed against cloth.

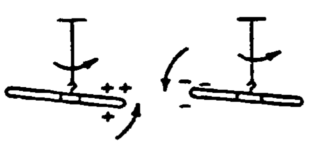
The flow of electrons is the *dynamic* form of electricity, a very valuable form of energy, which runs everything in this modern world from household appliances to heavy industrial equipment. "Reddy Kilowatt" well deserves the title "servant of mankind."



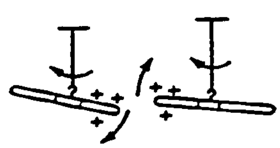
When glass is rubbed with silk it attracts small particles. The silk also attracts particles.



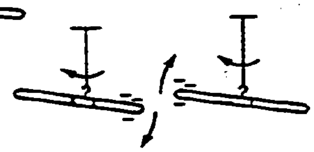
When two pieces of glass are rubbed with silk the two pieces repel each other.

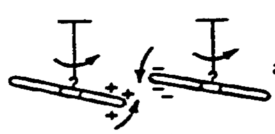


But a glass rod and a plastic or hard rubber rod, rubbed in the same way, attract each other.



Like charges repel





and unlike charges attract.

Conclusion: the charge that develops on the glass rod is different from that which develops on the plastic rod.

Why the spark to the door handle in the above example? The answer goes far to describe the nature of electricity. These electrons have been collected from the material in the plastic seat covers, but they are not content to stay where they have accumulated. Other objects in the car having fewer electrons are seen by them as unlike their own highly negative charge, and therefore attract them. They want especially to travel back into the electron deficient car seat covers, but cannot because materials like plastics, rubber, bakelite, dry air, porcelain, glass, etc., are such poor conductors of electrons that they are customarily used as insulators against electron flow. Travel is easy from the seat covers to the person by *static discharge*, but the reverse trip requires a different kind of travel, by *conduction*, and is almost impossible.

The car's metal parts also attract electrons, and once in the metal anywhere they can travel rapidly from one metal part to another, equalizing their charge throughout the car metal, which is their inclination. But they cannot travel this route until the person's body comes close to a metal part. They therefore continue to accumulate.

Because of their accumulated numbers they build up a pressure to escape. This compares to the pressure that a tall tank of water exerts to push water molecules through an open faucet at its base. Water molecules push harder through the faucet to get out as the water height in the tank increases. Similarly, the more electrons, the greater the pressure to escape.

ELECTRON PRESSURE

The pressure that electrons exert is called voltage, and measures their ability to push through a given resistance. Compare the electrical shock hazard of a 6-volt lantern battery with the standard 110-volt supply for house lighting. An electrical shock will hardly be felt from touching both terminals of the 6-volt battery, but this could easily be fatal with the 110-volt supply. The higher voltage is more able to push electrons through the body's resistance.

Back to the earlier example of static electricity, imagine now that the person's hand approaches the car door handle. The excess electrons,

attracted by the unlike charge in the metal door, rush to the finger tips. As the fingers approach metal, the airgap narrows. At some small gap width the voltage build-up suffices to overcome the reduced airgap resistance to electron flow, and the electrons push across in a spark.

Early in the century, researchers learned several important facts about the electron from their experiments with cathode-ray tubes. These are air-evacuated, sealed glass tubes, something like a light bulb with two metal electrodes to which wires are connected and which lead outside the bulb through sealed wall connections. If a high voltage is connected across the electrodes, a green glow appears at the electrode where the negative battery terminal connects. They observed that this glow came as rays from the cathode, or negative terminal, so they called them *cathode rays*. These rays could be deflected by a magnet and cast a shadow, from which they concluded that these particles had a negative charge and travelled in straight lines.

Researchers later determined the mass of the electron and the strength of the negative electrical charge in a series of classic experiments.*

Where are electrons when they are not moving in an electrical current? In 1897, J. J. Thomson postulated that they are embedded, like raisins in a bun, in the atom which he described as a sphere of positive electricity. Thomson's concept did not visualize that electrons actually revolve around the atom's nucleus. That electrons are basic parts of all matter was indicated from the different ways in which electrons can be produced. Their production by static discharge has been described here. In commercial electric power generation, electrons flow through a wire which cuts across magnetic lines of force; a simple magnet pushed through a coil of wire will duplicate the effect. In addition, electrons are ejected from metal surfaces when the metal absorbs either heat or light.

Niels Bohr contributed the next important information about the atom's electrons. In 1913 he described the atom as a simple planetary system with electrons that whirl about the nucleus in one or more circular orbits. His model depended upon and refined Thomson's concept and also incorporated Rutherford's idea of a positively charged atom nucleus.

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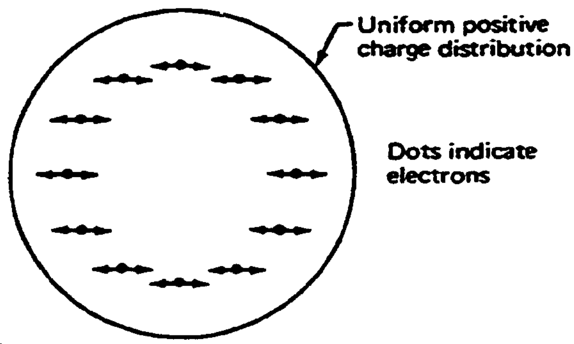
*For more information see *Sourcebook on Atomic Energy*, Samuel Glasstone, D. Van Nostrand Co., Princeton, N. J., 1967, 883 pp., $15.00.

Bohr's model, though it explained a few known facts about atoms, particularly the hydrogen atom, was not able to describe elements with large numbers of electrons. His oversimplified model assumed that the atom had only particle properties. These atomic particles, particularly electrons, actually have both particle and wave-like properties. Though the Bohr atom has been largely abandoned by physicists today, it can still help visualize some of the regularities of atomic phenomena, if not taken too literally.



Thomson's model of the atom

Any more precise description of atoms and their properties requires a mathematical treatment of their wave-like properties that is beyond the scope of this booklet. The reader may wish to see the indicated references for some information on the wave-mechanics of atoms.†

†*Basic Nuclear Physics*, Texas Atomic Energy Research Foundation, Fort Worth, Texas, Box 970, 76101, 1963, 43 pp. and *Physics* (Second Edition), Physical Science Study Committee, D. C. Heath and Company, Boston, 1967, 686 pp., $9.95.

CHEMICAL BONDS

Langmuir, the father of modern chemistry, tied together the ideas of his predecessors to explain the nature of the chemical bond between atoms. Electrons revolve around the atom's nucleus in neat and predictable patterns, and are restricted to and arranged in one or more successive "shells" around the nucleus. The first shell may contain 2 electrons, the second one 8, the third 18, and so on. However, the maximum number of electrons possible in any outer-most shell is 8.

Further, the number of outer-shell electrons is fixed and remains constant for each particular kind of atom. For example, sodium has one outer-shell electron, and chlorine has seven. This remains true despite the atom's ability to temporarily lose or gain outer-shell electrons, becoming, respectively, positively or negatively charged. Such a charged atom, called an *ion*, cannot exist for long and, by the law that opposite charges attract, will eventually either gain or lose electrons to again become electrically neutral. Hence, the atom must retain its specified number of outer-shell electrons. They are part of the negative electron charge the atom must have to exactly balance the positive nucleus charge, as will be described later.

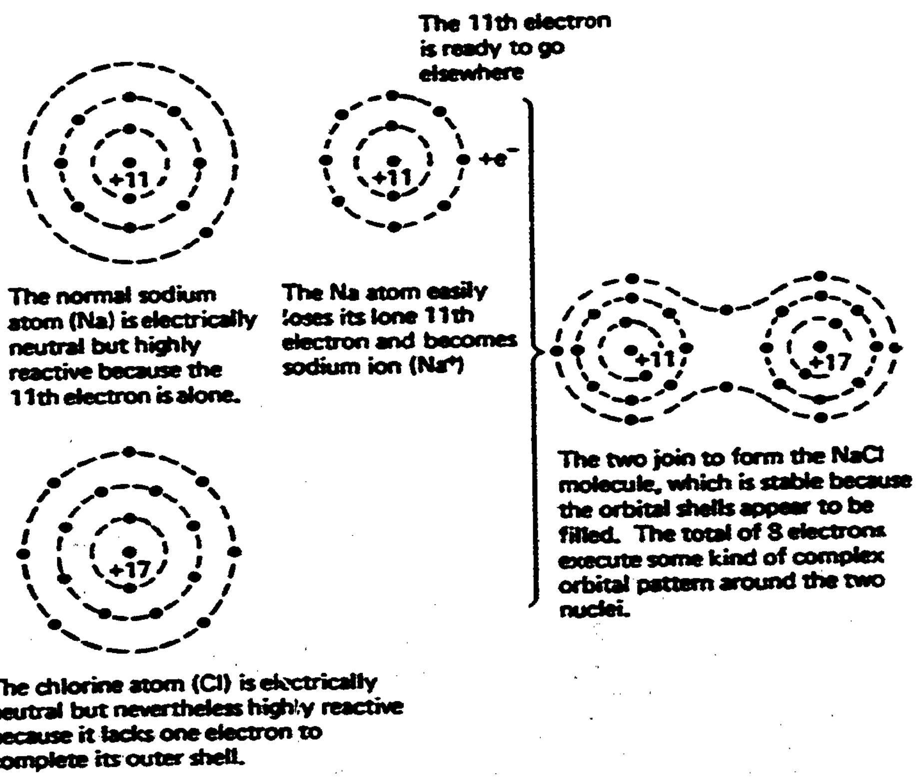
Atoms are prodded in another direction as to how many electrons allowed in their outer orbits. They would like to reach the *saturated*—all slots full—condition of eight outer-shell electrons. The smaller the number of outer-shell electrons in an atom, the greater the prod, that is, the more chemically active. Hydrogen and sodium, for example, with only one electron in either of their outer shells, react with other elements so quickly they can explode.

In the only kind of permanent arrangement that nature allows to satisfy this urge, atoms add more electrons to their outer shells by chemically combining with other kinds of atoms. They satisfy their mutual craving for electrons by sharing their outer-shell electrons. The chemical reaction between sodium and chlorine illustrates this. The product is sodium chloride, commonly known as table salt.

The bond between atoms of a chemical compound was thus explained by reference to the nature of electricity. In both a chemical reaction and in a flow of electricity, the atom's nucleus and inner-shell electrons remain unaffected. Only the outer-shell electrons of an atom can move through a conductor to become part of an electrical current.

And, only these same outer-shell electrons are shared between atoms to constitute a chemical bond between atoms. When atoms join together to form molecules, they share their outer-shell electrons. All chemical reactions are caused by electrons in the atom's outer shell.

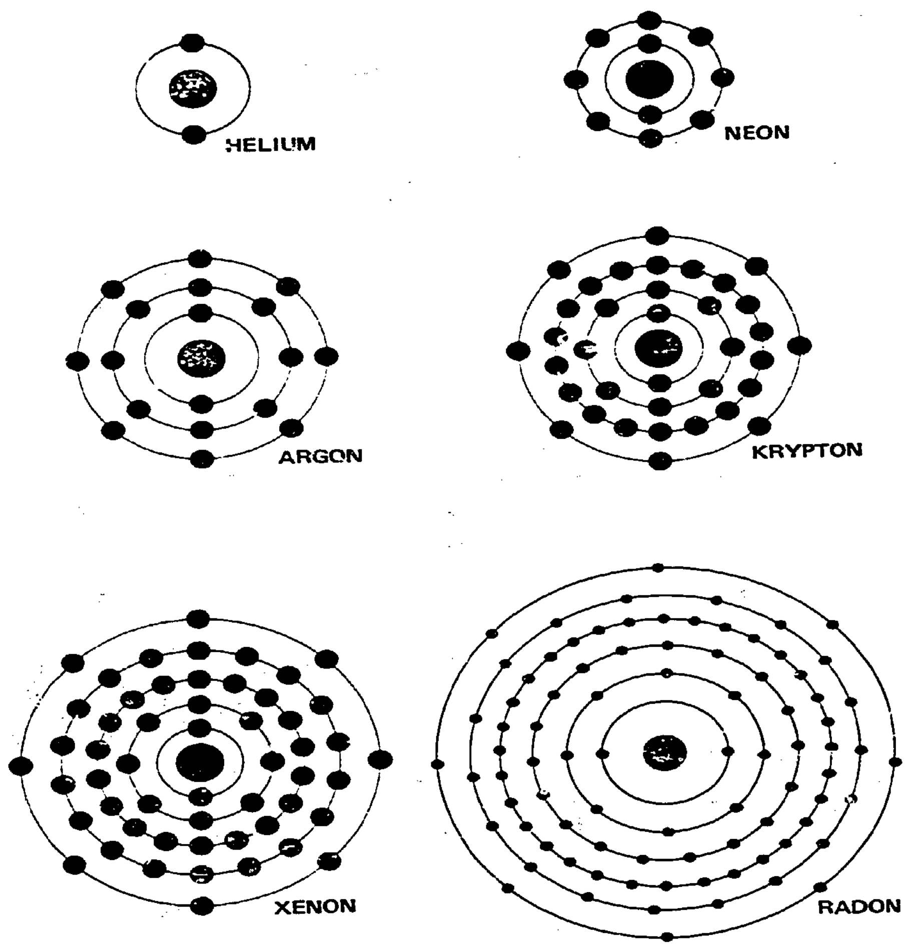
Some bonds between atoms are tighter than others. The tighter the bond, as in sodium chloride, the more stable the compound. When atoms change from a loose bond to a tighter bond arrangement, they give up energy in the form of heat, electricity, etc. For example, natural gas is mainly a loosely bonded mixture of hydrogen and carbon atoms. When burned, the hydrogen and carbon atoms, already separated at the fire's high temperature, combine with oxygen in the air to yield water vapor and carbon dioxide, and to emit heat. Both these product compounds are very stable compared to the original gas, so much so that energy must be supplied to separate either water or carbon dioxide back into hydrogen and carbon.



In the schematic illustration above, reactive sodium, in combination with chlorine, has formed chemically stable sodium chloride. The existing abundance of salt—in the oceans, on the salt flat beaches, as

mined from the earth—proves its chemical stability; if not, it would have recombined with other of nature's chemicals to produce similar abundances of other sodium compounds. Energy must be added to separate the sodium and chlorine atoms, as in the electrolysis of sodium chloride.

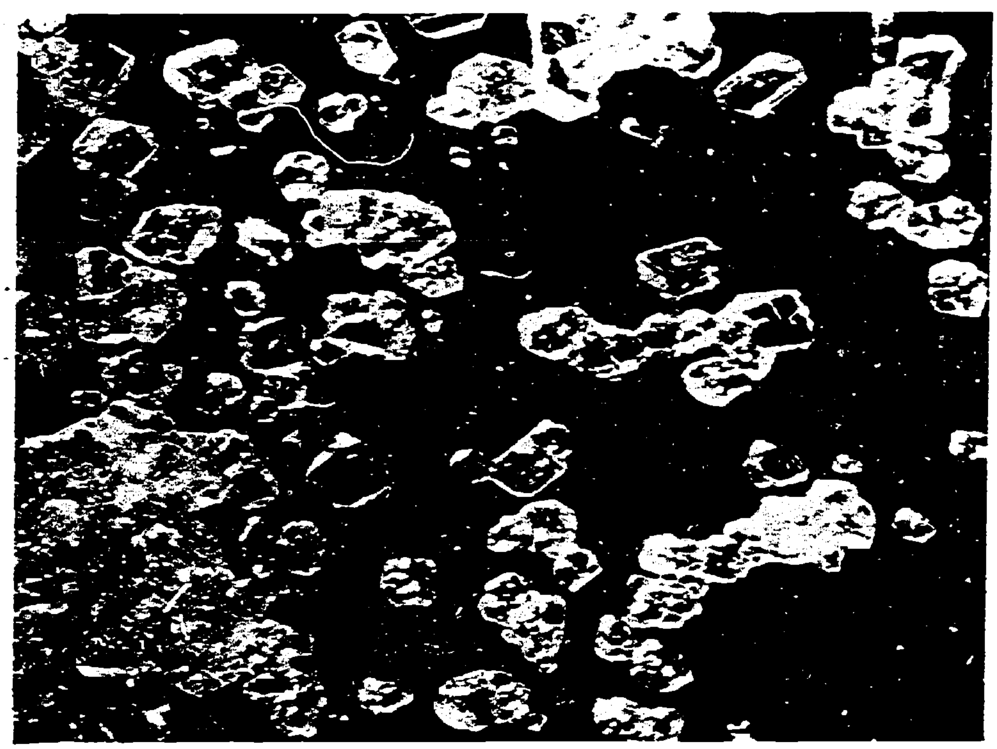
On the other hand, the fact that sodium does not exist naturally as a free metal proves its instability. When industrially produced, it must be carefully protected, usually with a blanket of *inert* gas, from quickly reacting with oxygen or water vapor in the air.



Schematic of electron configurations in the inert gases

THE INERT GASES*

The six naturally occurring gaseous elements with full outer shells are helium, neon, argon, krypton, xenon, and radon. Their electron configurations are illustrated schematically here. All have outer shells of 8 electrons, except helium which has only 2. Called rare, inert, or noble gases, they were until recently thought incapable of chemical reaction with any element or compound, because elements with saturated outer rings are supposed to be chemically inert, as all previous experience had indicated.



Crystals of xenon tetrafluoride

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*For more information see *The Chemistry of the Noble Gases*, an Understanding the Atom booklet.

Then in 1962, Neil Bartlett, a young British chemist, acting upon a hunch, placed platinum hexafluoride, a very reactive gas, in contact with xenon gas. In so doing he shattered one of the accepted and revered dogmas of chemistry. A true chemical compound of xenon, platinum, and fluorine was formed. Since then other fluoride and oxygen compounds of xenon have been formed, and one fluoride compound of radon.

As for helium, neon, and argon, all evidence still shows that these gases are indeed inert. The rule, that elements with saturated outer electron shells are chemically non-reactive, therefore still generally applies. The only exceptions are xenon, krypton, and possibly radon, and then only as they react with the highly reactive fluorine and oxygen elements.

COMPLEXES OF XENON AND KRYPTON FLUORIDES

Noble Gas Compound	XeF_2	XeF_4	XeF_6	$XeOF_4$	KrF_2
Complexing Fluoride	Ratio of Noble Gas Compound to Complexing Fluoride				
NaF	*	*	1:2	*	*
KF	*	*	1:2	1:3 1:6	*
RbF	†	†	1:2 1:1	2:3	†
CsF	†	†	1:2 1:1	1:3 2:3 1:1	†
SbF_5	1:2	‡	1:2 1:1 2:1	1:2 † †	1:2
AsF_5	*	†	1:1	2.1§	‡
BF_3	*	†	1:1	*	†
TaF_5	1:2	†	†	†	†
VF_5	*	*	2:1	‡	†

*No compound formed.
†Has not been tried.
‡Compound forms; formula not yet known.
§Unstable above −20°C.

THE NUCLEUS*

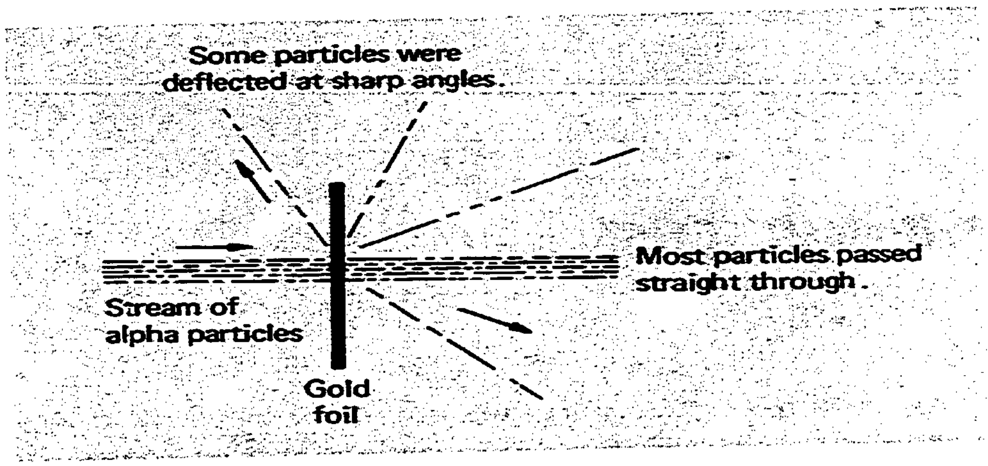
In 1900 Lord Rutherford suggested that a positively charged nucleus kept the negatively charged electrons attached to the atom. He and others reasoned that the atom's nucleus must be positively charged to balance the negative charge of the electrons. This was deduced since atoms were observed to be neutral. Rutherford also recognized that the atomic nucleus was a hard dense core and contained most of the atom's mass.

Ernest Rutherford, 1871-1937

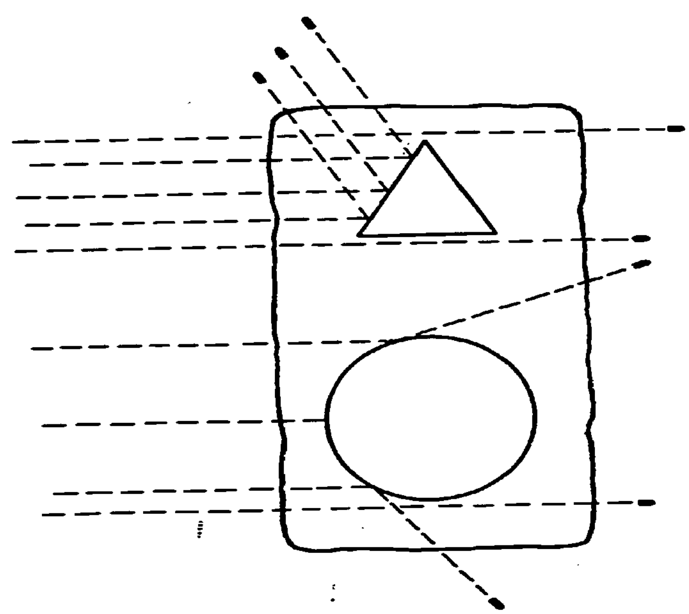
Next, from their x-ray bombardment of many chemical elements, researchers noticed that the same particle always emerged—the hydrogen atom minus its electron. Hydrogen, simplest of the elements, has one particle in the nucleus, with one electron orbiting it. The particle which emerged, an essential part of every atom's nucleus, was the hydrogen nucleus. This was the positively charged particle for which Rutherford had searched. They named this

*For more information see Understanding the Atom booklets, *The Chemistry of the Noble Gases* and *Radioisotopes in Medicine*.

particle the *proton* from the Greek word meaning "first" because hydrogen is the first in an element series that was now seen to exist.



Rutherford's most famous experiment, which led him to the concept of the nucleus.



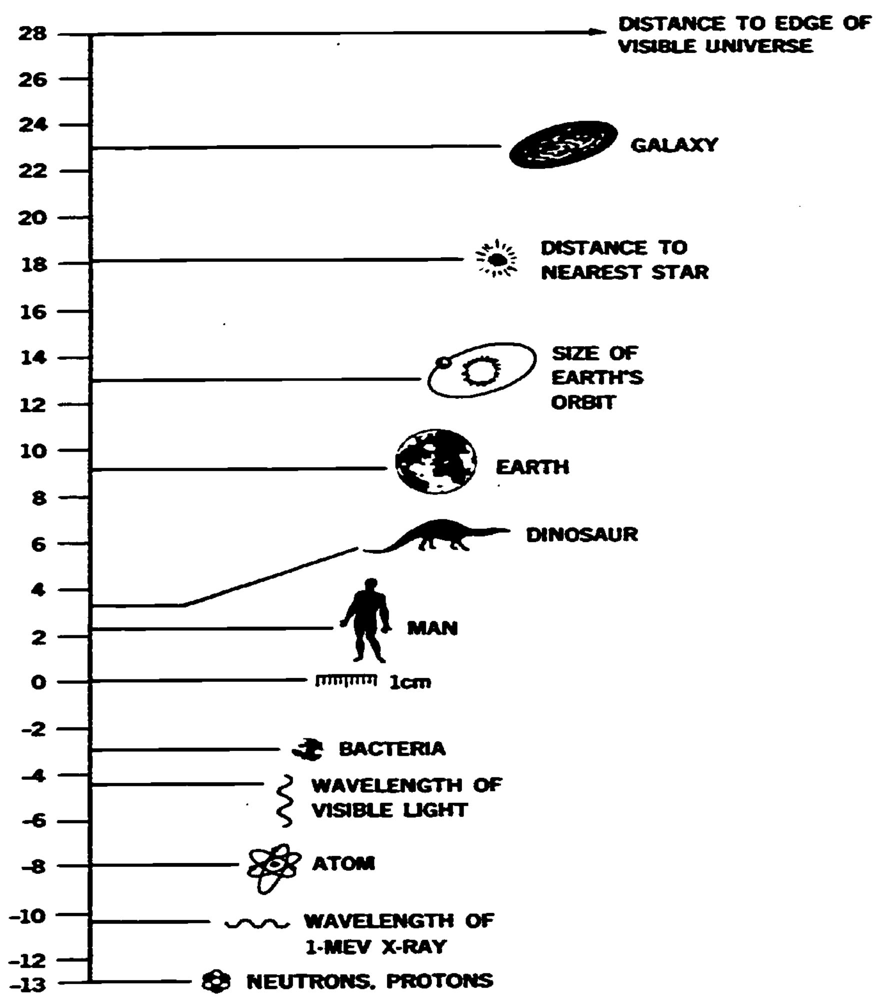
Probing inside a bale of hay with bullets. The paths of the bullets tell us where pieces of matter may be located in the hay, and something about their shapes.

From this information they deduced these new discoveries: (1) the proton, in addition to being the nucleus of the hydrogen atom, is also one of the "building blocks" of the nuclei of all other atoms, (2) the proton has the positive charge which neutralizes the negative charge of one electron, (3) there is one proton in the nucleus of each atom for each electron outside the nucleus, and (4) a smoothly ascending series of the elements is defined by assigning an *atomic number* to each element equal to the number of protons in its nuclei.

There proved to be yet a third "building block" of nature in this amazing electrical association. Discovery of the *neutron* in 1932 by Sir James Chadwick completed much of what we know now about the atom's structure.

The neutron, discovered through the bombardment of various elements with x-rays, was at first thought to be a ray because it was not deflected by magnetism, as were protons and electrons. But, unlike a ray, its slower travel and its push against other particles showed it to have a mass. Since it is not deflected by magnetism, it was seen to be electrically neutral. For this reason it was called a neutron.

SIZE OF OBJECTS IN UNIVERSE



Where each number is an exponent of 10 centimeters (cm):

-2 means $(10)^{-2} = 0.01$ cm
0 means $(10)^{0} = 1$ cm
2 means $(10)^{2} = 100$ cm
6 means $(10)^{6} = 1,000,000$ cm
etc.

VISUALIZING THE ATOM

How do we visualize an atom whose orderly and precise arrangement is the basic constituent of every material thing on earth and in the universe? Imagine the protons and the neutrons in the atom's nucleus. The electrons are orbiting the nucleus.

Note the atom's exceedingly small size!* The term *hairsbreadth* signifies about the smallest size that can be seen or felt, or indeed to many people that is at all worth any concern. The atom is *much* smaller, beyond the range of our best microscopes, though a big molecule like the tobacco mosaic can be seen. Atoms are about a million times narrower in diameter than a hairsbreadth. Since all materials are built of atoms, any material big enough to be seen and touched, even a hair, must consist of a vast number of atoms. The electrons are so small that if a gallon of water were magnified to the size of the earth, the electrons could barely be seen with a good microscope.

But what keeps these electrons from flying out of their orbits? Two kinds of mutual attraction between the atom's nucleus and its electrons

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*For more information see *Microstructure of Matter*, an Understanding the Atom booklet.

prevent this. One force of attraction exists because of the masses of the nucleus and the electrons, much as the gravitational attraction exists between the sun and the earth, because of the mutual attraction between their masses. The same force of mutual attraction, because of mass, will pull together small particles floating on still water. Another mutual attraction exists between the protons and electrons because of their different electrical charge. Unlike electrical charges attract each other; therefore protons attract electrons.

The electron is not pulled into the nucleus because of the speed at which it revolves around the nucleus—again something like our earth and sun. Our speed in revolving as a heavy object around the sun keeps pulling us away from the sun, but the gravitational force between the earth and sun holds us together. The same intricacy, precision, and orderly arrangement we see in the universe repeats in the submicroscopic scale of the atom.

Another amazing similarity between our solar system and the small world of the atom is the tremendous volumes of empty space, in both, compared to the relatively small volumes of solid material they contain. There is much space between the sun and the earth—93 million miles—compared to the diameters of these bodies. The same on a relative basis is true of the atom's nucleus and its electrons. As true of the atom, so also of the molecule.

Envision, for example, the ordinary hydrogen atom, one proton in the nucleus about which one electron whirls. If this atom were enlarged so that the proton were baseball size, the electron would be at a distance, equal to the length of about eight football fields, away. The atom is almost all empty space.

There is also much space between atoms in the molecule, and between the molecules themselves. If all the empty space were eliminated in the body of a 200-pound man, he would not be any larger than one dust particle. Furthermore, the earth without the space in its molecules and atoms would be a ball only a half mile in diameter.

THE CHEMICAL ELEMENTS*

ATOMIC NUMBER

Each element has an *atomic number* which, by definition, equals the number of protons in that element atom's nucleus. The atomic number also equals the number of electrons outside that atom's nucleus, since the atom is electrically neutral. For example, oxygen has 8 protons (plus 8 neutrons) in its nucleus, an atomic number of 8, and 8 electrons outside the nucleus. The atomic number of an element—the number of protons or electrons—is different for each element, and increases in exact increments of 1 for each of the 105 elements, from 1 for hydrogen to 105 for the most recently discovered element.

*For more information see Understanding the Atom booklets, *Our Atomic World; Rare Earths, the Fraternal Fifteen; Synthetic Transuranium Elements*; and *Sourcebook on Atomic Energy*, Samuel Glasstone, D. Van Nostrand Co., Princeton, N. J., 1967, 883 pp., $15.00.

ATOMIC WEIGHT

A new weight scale was defined to determine and record the atomic weights of the elements. As the initial step the oxygen atom was selected as the standard by assigning it the weight of 16 *atomic mass units* (amu). The atomic weights of the other elements were then determined by various methods. They vary, for example, from 1.00867 amu for hydrogen, to 261 amu for the heaviest of three isotopes of element 104 that have been discovered.

Upon this basis the three fundamental particles have these weights:

Mass of neutron = 1.00893 amu
Mass of proton = 1.00812 amu
Mass of electron = 0.00055 amu

As seen here, protons and neutrons in the atom's nucleus account for most of the atom's mass or weight. The electron weight can almost be disregarded since each weighs only about $\frac{1}{2000}$ of either a proton or a neutron.

The usual scales were too unwieldy to measure the atom's ultra-light weight. A gram of any material contains exactly 6.0225×10^{23} amu (28 grams make an ounce). This large number written out is 602,250,000,000,000,000,000,000. To have used units of *grams*—the smallest scale then available—to measure the atom's weight would have been unwieldy as using units of *tons* to measure small portions of garden seeds that sell in ounce-size packages.

The large number above has a significance which does not appear in the example shown. Called the *Avogadro number*, this is an important and fundamental constant of physical chemistry. There are 6.0225×10^{23} molecules in the molecular weight of any material expressed in grams. Oxygen, for example, has a molecular weight of 32 amu (2 atoms per molecule at 16 amu per atom, since all the element gases have 2 atoms per molecule). The molecular weight of oxygen expressed in grams is 32 grams. There are therefore 6.0225×10^{23} molecules in 32 grams of oxygen. Sodium has a molecular weight of 23 amu, so 23 grams of this element also contain 6.0225×10^{23} molecules. The number of molecules in other compounds, or even mixtures of compounds, can be similarly determined.

The electrons of an atom, though not important in the weight they contribute to an atom, however do solely determine its chemical properties. Since atoms with the same number of electrons have identical chemical properties, all atoms of an element have identical chemical properties.

ISOTOPES

Atoms of the same element can differ only because of their weight, and this difference arises because their nuclei contain slightly different numbers of neutrons. Such atoms of a particular element, with the same atomic number but different atomic weights, are that element's *isotopes*, from the Greek *isos* meaning *same* and *topos* meaning *place—same place*. Every element has three or more isotopes. The number of protons and electrons in any one isotope of an element are the same as in every other isotope of that element. Having the same number of electrons, they differ only physically, not chemically. They can therefore be separated from one another only through their physical differences such as freeze-points, weights, etc.

There are probably more than 1400 total natural and man-made forms of the elements including all the known isotopes. Of these 1400, over 280 *stable* isotopes and over 40 *radioactive* isotopes exist naturally. The some 1100 remaining isotopes are radioactive and have been produced artificially in the new machines of this Nuclear Age, the nuclear reactors and the cyclotrons.* *Radioactive* means they emit energetic nuclear radiation, a term to be defined more completely later. *Stable* means they are not radioactive.

The different isotopes of oxygen, carbon, and hydrogen—three of the most abundant elements on the earth's surface—illustrate a few of the isotopes found in nature.† These naturally appearing isotopes are distributed in set proportion throughout the earth. Besides the

*For more information see Understanding the Atom booklets, *Nuclear Reactors*, and *Accelerators*.

†For more information see Understanding the Atom booklets, *Radioisotopes and Life Processes*, and *The Natural Radiation Environment*.

abundant oxygen-16 isotope, there are two other less abundant oxygen isotopes with weights of 17 and 18. All are stable. Two of the carbon isotopes, carbon-12 and carbon-13, are stable. Carbon-14, one of the most important of all radioisotopes, is radioactive. Carbon-14 forms naturally from cosmic ray bombardment of nitrogen in the air.

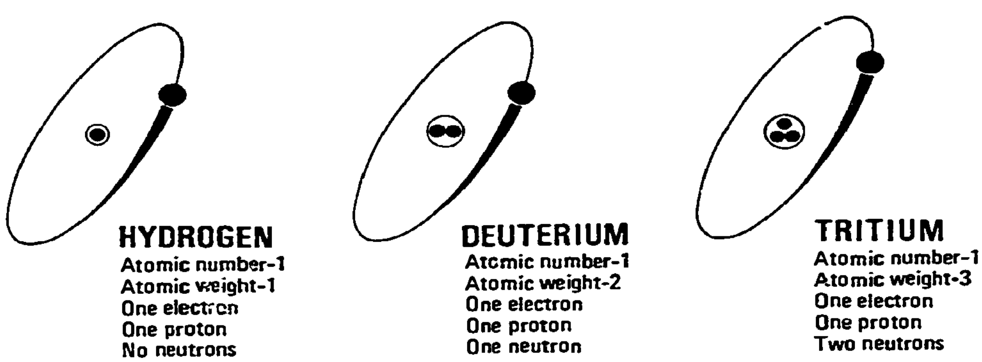
Hydrogen appears in nature as three radioisotopes, two stable and one radioactive. Hydrogen-1 is the most abundant. Hydrogen-2, called deuterium, occurs in ordinary water in the ratio of about one pound in every three tons of plain water, and contains a neutron and a proton in its nucleus. Hydrogen-3, called tritium, with two neutrons and one proton, the only radioactive isotope of hydrogen, forms in nature by cosmic ray bombardment of nitrogen in the air, and is used extensively in biological and medical research.

SOME RADIOISOTOPES PRODUCED BY COSMIC RAYS

Isotope	Half-life	Concentration (dis/min/cu.m)*
Tritium-3	12.3 yrs.	10^{1}
Beryllium-7	53 days	1
Beryllium-10	2.7×10^{6} yrs.	10^{-7}
Carbon-14	5760 yrs.	4
Sodium-22	2.6 yrs.	10^{-4}
Silicon-32	700 yrs.	2×10^{-6}
Phosphorus-32	14.3 days	2×10^{-2}
Phosphorus-33	25 days	1.5×10^{-2}
Sulfur-35	87 days	1.5×10^{-2}
Chlorine-36	3×10^{5} yrs.	3×10^{-8}

*Disintegrations per minute per cubic meter of air in the lower troposphere.

THE THREE ISOTOPES OF HYDROGEN



ENERGY COMPARISONS

Energy is the capacity to perform work, and work results when a force *moves* a mass. By definition, no work can be performed, regardless of the energy expended, without movement. For example, if a strong man pushes against a rock, he performs no work regardless of the effort he expends unless he moves the rock. Energy takes many forms—such as mechanical, light, heat, chemical, electrical, sound, and nuclear.

Energy can be readily converted from one form to another. For example, the burning of coal turns chemical energy into heat, which can boil water to produce steam, which can turn steam turbines to produce mechanical energy. Steam turbines turn generators to produce electrical energy, today's most useful and adaptable form of energy. Electrical energy produces light or heat, turns motors, and performs a multitude of other useful tasks.

Every form of energy can be regarded as either *kinetic* energy, or *potential* energy, or both. The kinetic energy of a body or particle is energy of *motion*, whereas potential energy is that of *position*, relative to other bodies. Potential energy can be readily converted into kinetic energy. The tremendous fossil fuel reserves—the sun's energy accumulated over the years—have until the advent of applied nuclear

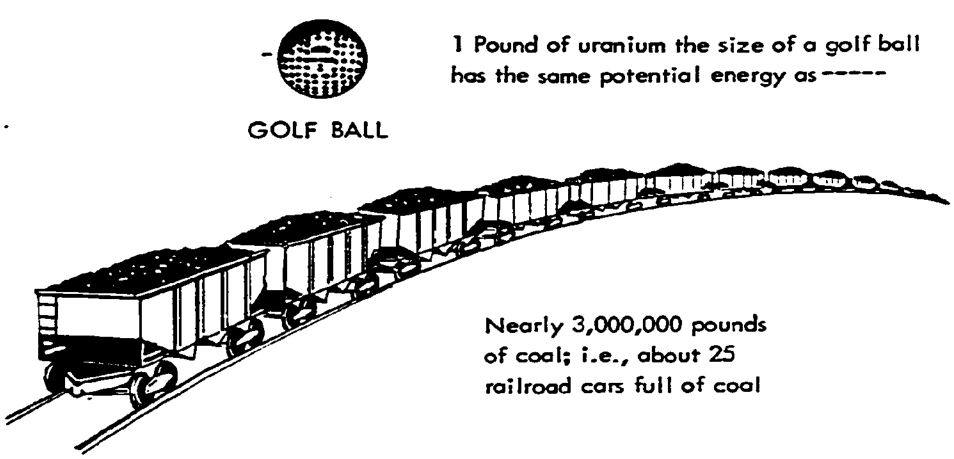
energy represented the world's only significant source of useful potential energy for producing large amounts of power.

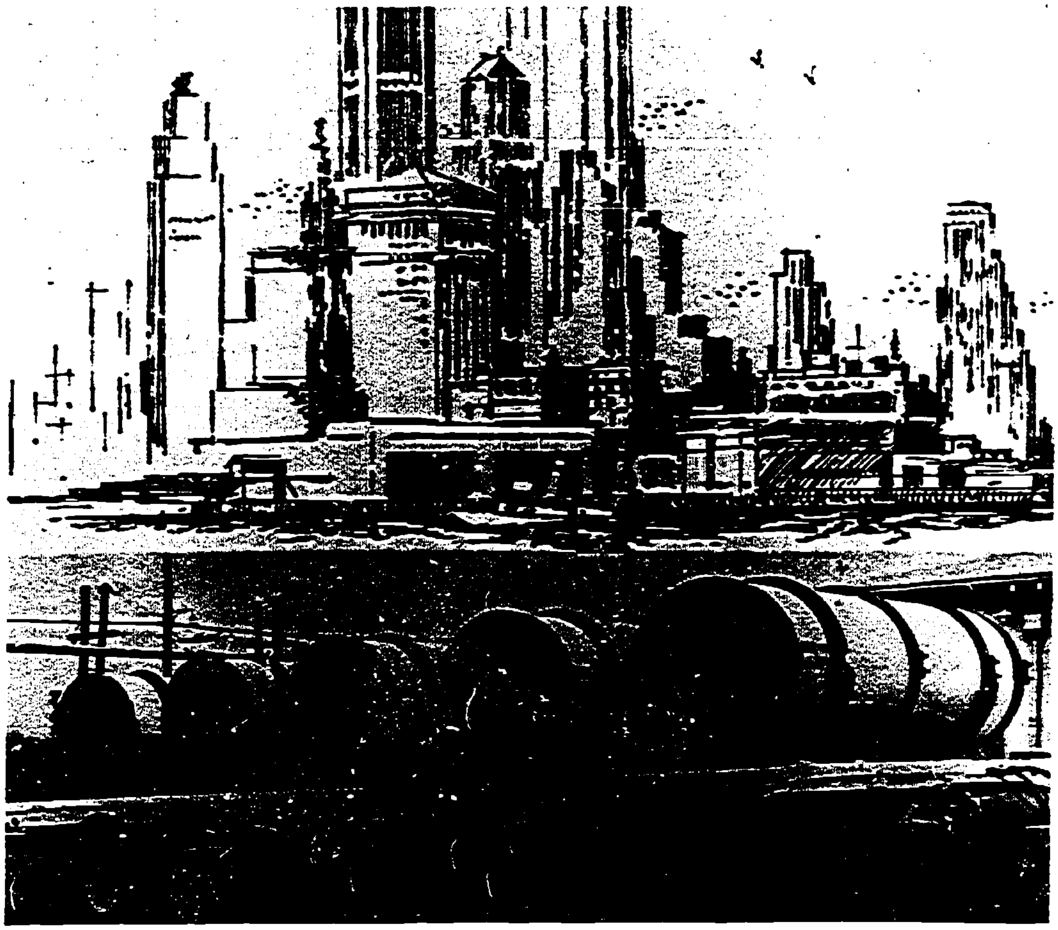
There is potential energy in many kinds of common materials. Water, if dropped from a height will turn a turbine that generates electricity. The potential energy stored in coal, oil, and natural gas becomes useful when these fuels chemically combine with oxygen by burning to produce heat. There is potential energy in a chemical storage battery which is released by electrical connection to household appliances or fixtures to light, heat, or move devices that perform useful work. There is potential energy in a stick of dynamite; when a chemical reaction of the chemically unstable materials is triggered, the dynamite explodes.

Each different form of energy can be classified as either physical, chemical, or nuclear energy. Falling objects expend physical energy; burning fuels or a storage battery in operation expend chemical energy; and uranium metal fissioning in a nuclear reactor expends the internal nuclear energy of the atom.

SOME COMPARISONS OF MAGNITUDE

1 Pound of any body with 100 feet to fall has	.000037	kw-hr
1 Pound traveling 100 feet per second has	.0000588	kw-hr
1 Pound of water when formed from H_2 and O_2 releases	2.00	kw-hr
1 Pound of coal (heat of combustion 12,000 Btu/lb) releases	3.52	kw-hr
1 Pound of gasoline (heat of combustion 20,000 Btu/lb) has	5.52	kw-hr
1 Pound of TNT (1/8 heat of combustion of coal) has only	.44	kw-hr
1 Pound of U-235 or Pu-239 consumed in the fission process yields	11,400,000.00	kw-hr
1 Pound of hydrogen converted to helium yields	85,352,000.00	kw-hr





A single truckload of enriched uranium-235 like this shipment can supply the total electrical power needs for a city of 200,000 people—such as Mobile, Alabama or Tacoma, Washington—for an entire year.

Now briefly in the previous table, compare the different amounts of physical, chemical, and nuclear energy expended by one pound samples of some materials, chiefly fuels. Note the enormous advantage, on this basis, of nuclear over the more conventional energy sources. Energy is measured here in terms of kilowatt-hours, the units in which the ordinary home electric meter is read. For comparison, a 100-watt light bulb burning for 1-hour uses 0.1 kilowatt-hour. The average home in the United States, with its many appliances, requires 250 to 300 kilowatt-hours per month.

A piece of uranium the size of a golf ball has the same amount of nuclear energy available through fission that 25 carloads of coal have if burned. A single truckload of uranium will supply the total power needs for a city of 200,000 for one year.

EQUIVALENTS AND CONVERSION FACTORS

Work and energy 1 joule (j) = 10^7 ergs = 0.239 calorie (cal) = 0.7376 ft-lb
1 cal = 4.18 j = 3.087 ft-lb
1 Btu = 252 cal = 778 ft-lb = 1055 j
1 kilowatt-hour (kwh) = 3.60×10^6 j
1 electron volt (ev) = 1.60×10^{-19} j
1 Mev = 10^6 ev

Power 1 horsepower (hp) = 0.746 kw = 550 ft-lb/sec
1 watt (w) = 1 j/sec = 0.738 ft-lb/sec

Heat 1 Btu/lb = 0.556 cal/gram

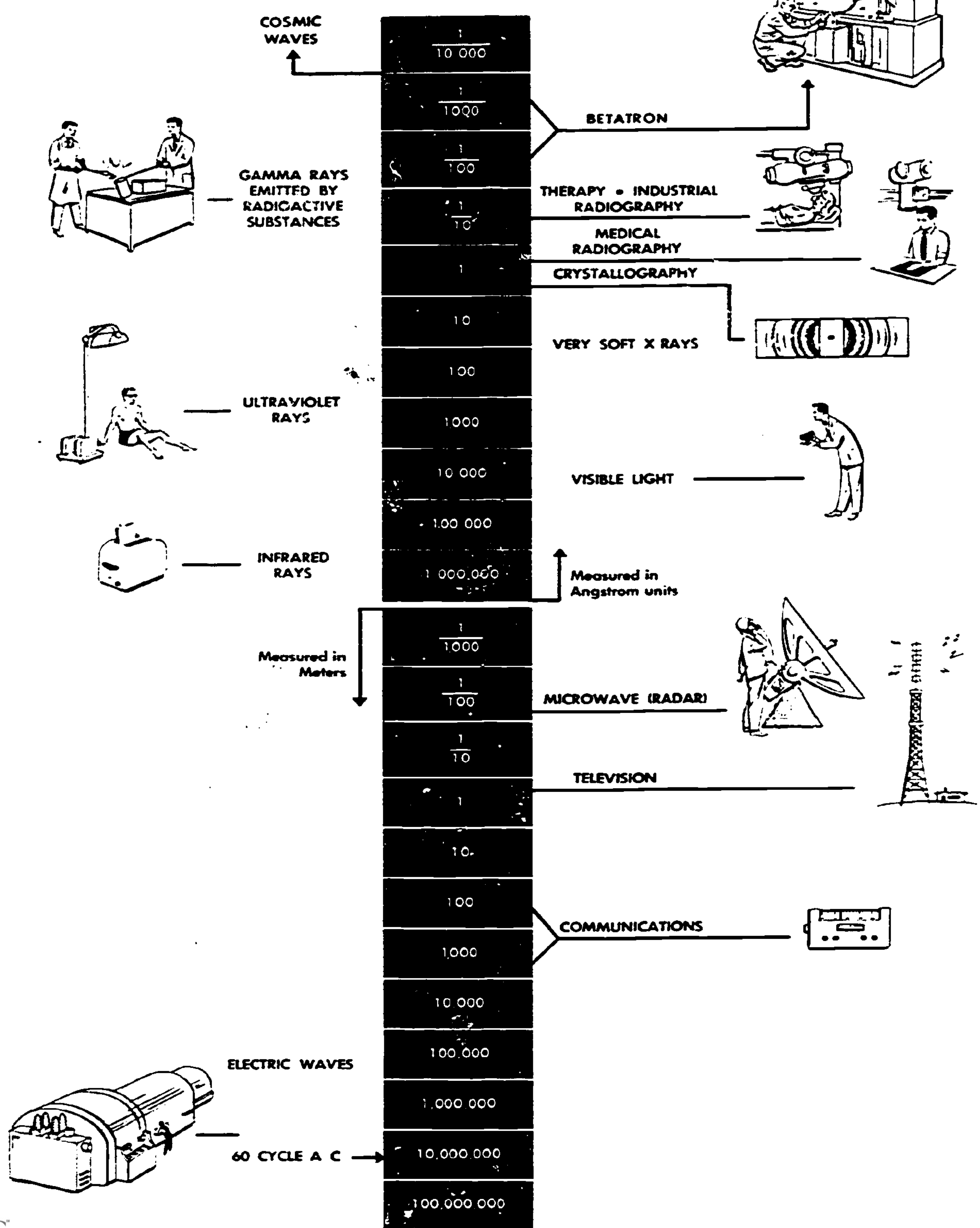
RADIOACTIVE ATOMS EMIT NUCLEAR RADIATIONS

Radiation means to transmit energy through space or matter, and also refers to the energy that can be so transmitted. There are two general types, *waves* with no mass which surprisingly display both particle-like and wave-like behavior, and *particles* with definite masses. Waves include, for instance, ordinary visible light rays,* infrared rays which can be seen and felt as heat, and ultraviolet light which cannot be seen or felt. These energetic electric and magnetic waves travel through space at the fantastic speed of 186,000 miles per second and interact with matter.

Man has always been exposed to *nuclear radiations* from atoms made radioactive by nature. Nuclear radiations, characteristically more penetrating than light and heat and ultraviolet light, and together with

*For more information see Understanding the Atom booklet, *Lasers*.

THE ELECTROMAGNETIC SPECTRUM



them, are part of his natural radiation background.* Stars including our sun are intensely radioactive, our earth now only slightly so. High-energy cosmic rays and particles from outer-space constantly bombard the earth's surface. A number of radioactive atoms widely distributed throughout the earth are part of many common materials—rocks, soil, plants, animals—even intimately part of man himself.†

The energy rays that radiate from radioactive atoms include several kinds of waves and particles.‡ Man-made *x-rays* were first discovered in 1895 and are emitted from the atom's orbital electrons when high energy electrons strike a metal target. X-rays are the only radiation that can properly be termed *atomic* radiation since all other radiations come from the nucleus and are therefore more precisely called *nuclear* radiations.

Nuclear radiation from radioactive atoms was discovered quite accidentally, one year after x-rays, by the French physicist, Becquerel. While experimenting with a large number of chemical compounds, he discovered that the radiation from uranium would darken a photographic plate. Within 2-years, radium, another naturally occurring radioactive element, was isolated from pitchblende ore, the primary source also of uranium.

Henri Becquerel, 1852-1908

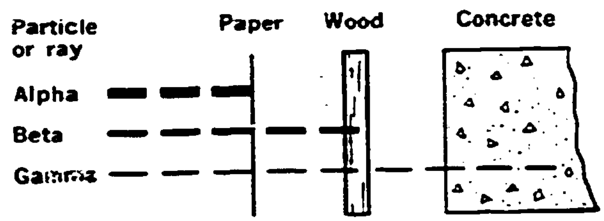
Both radium and uranium emit *alpha particles* from their nuclei in a *nuclear reaction* by which mechanism they decay radioactively to lose weight, and thus become *transmuted*—changed—into other chemical elements. Alpha particles are slow moving and relatively massive charged particles of 2 protons and 2 neutrons, identical to the helium atom's nucleus. In the process of radioactive *alpha decay* these two elements emit other more penetrating radiations called *gamma rays*, similar to x-rays except that they

*For more information see Understanding the Atom booklets, *The Natural Radiation Environment*, and *Space Radiation*.

†For more information see Understanding the Atom booklet, *Your Body and Radiation*.

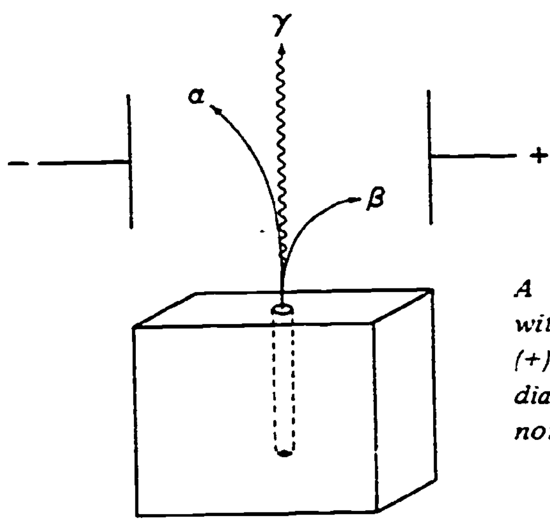
‡For more information see Understanding the Atom booklets, *Microstructure of Matter*, and *The Elusive Neutrino*.

originate in the atom's nucleus. Gamma radiation can penetrate several inches of lead, depending upon its energy. Alpha particles, however, can be stopped easily by the thickness of a sheet of paper or by the horny outer layer of human skin.



Relative penetration of alpha, beta, and gamma radiation

The *beta particle*, a negatively charged particle identical to the electron, is another principal form of nuclear radiation; and *beta decay*, another nuclear reaction by which radioactive atoms transmute into other elements. The beta particle, unlike the electron, emits from the nucleus undergoing beta decay when a neutron spontaneously changes



A radium sample in a lead box with a small opening emits alpha (+), beta (−), and gamma (±) radiation. The gamma radiation is not affected by the electric field.

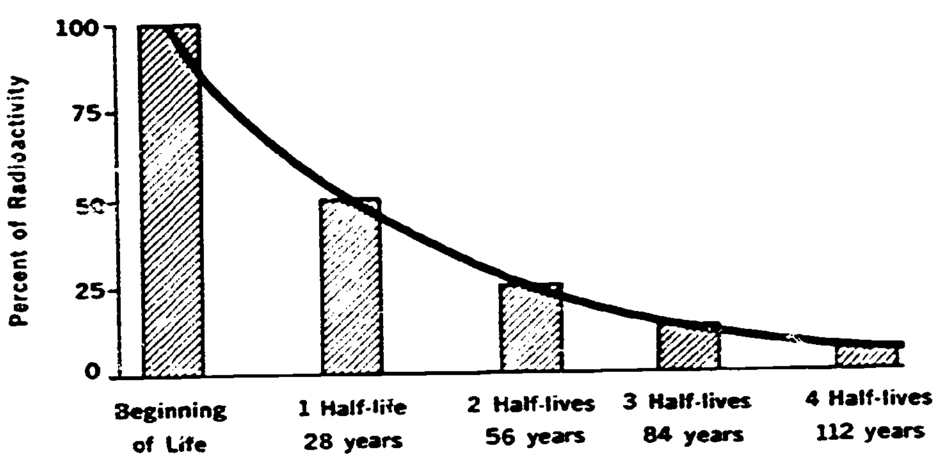
into a proton and a beta. Carbon-14 and deuterium are two of the many pure beta emitters. Betas penetrate less deeply than gamma radiation, but will penetrate about 100 times deeper than alphas. Betas can be stopped, for example, by an inch of wood or by a thin sheet of aluminum foil.

Neutrons, another kind of nuclear radiation, sustain the fission chain reaction in nuclear reactors, as will be described later.

THEIR HALF-LIVES*

All radioactive atoms decay spontaneously, at a specific and steady rate which is different for each radioactive isotope. The rate is independent of any physical or chemical condition like temperature, pressure, physical state or sample size, or kind of chemical combination with other atoms. Radioactive decay is measured by the number of disintegrations that occur per unit of time. The time required for any radioisotope sample to lose half its radioactivity—that is, for one-half of the atoms in the sample to disintegrate—is its *half-life*. Half-life values can be precisely measured for the different radioactive isotopes, and range from less than a millionth of a second to billions of years.

Half-life pattern of strontium-90

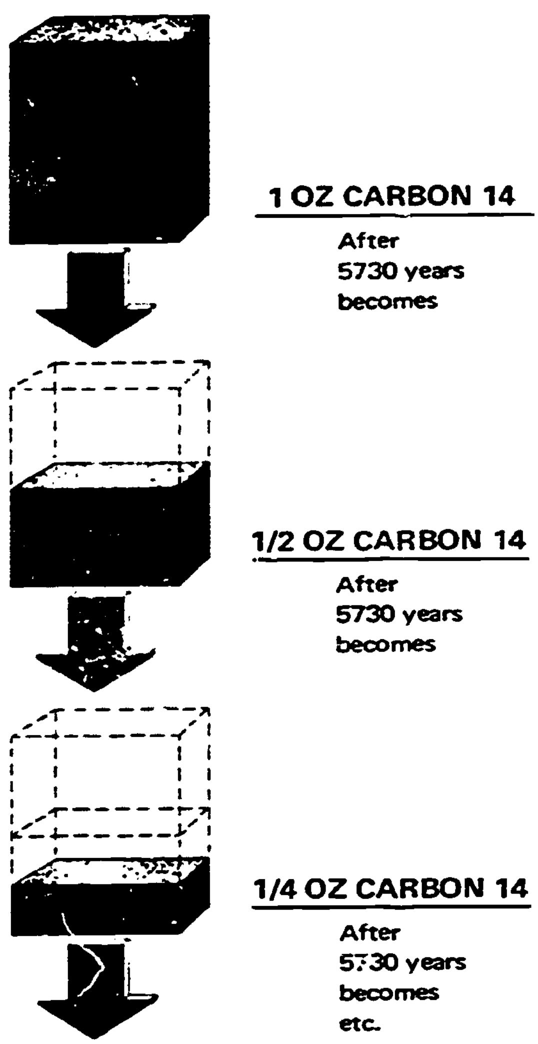


Carbon-14, for instance, has a half-life of 5730 years, which means that any size carbon-14 sample will lose half its carbon-14 atoms in 5730 years.†

*For more information see Understanding the Atom booklet, *Radioisotopes in Medicine*.

†For more information see Understanding the Atom booklet, *Nuclear Clocks*.

These carbon-14 atoms have changed to stable nitrogen-14. After another 5730 years half of the remaining carbon-14 atoms will have changed to nitrogen-14, which would leave one-fourth as many carbon-14 atoms as originally. Uranium atoms have half-lives of billions of years. Such a long half-life means that most of the original uranium, laid down in past geological ages, still remains today.

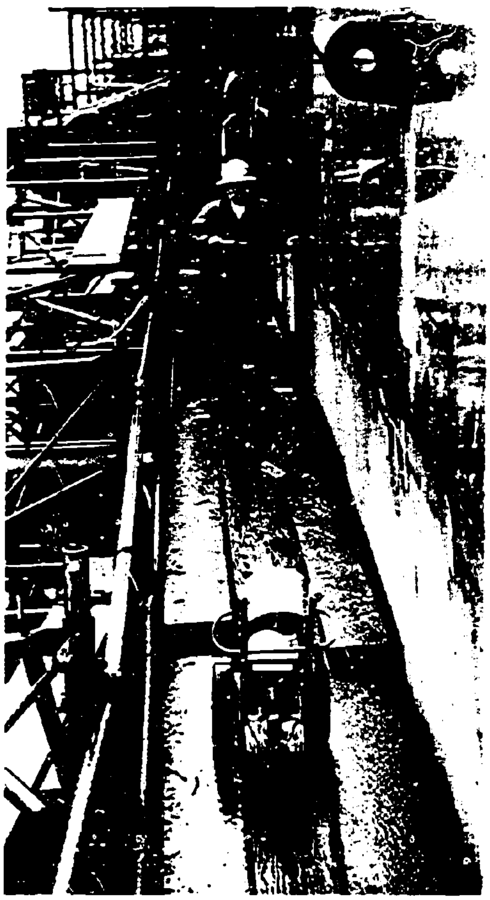


THEIR VERSATILE PROPERTIES

Radioisotopes are able to perform many different tasks in medicine and industry* today because of their versatile characteristics. Many of the approximate 1100 radioisotopes which have been produced artificially are available now in commercial quantity. Over 40 occur naturally. Collectively, they cover a broad range of chemical and radiation properties. The radiation form, whether alpha or beta or gamma, the energy level, and the half-life each vary naturally from isotope to isotope, even for isotopes of the same element. There is such a considerable variety that one or more isotopes can usually be found with almost any set of specific chemical and radiation characteristics needed for a particular radiation application.

For example, nuclear medical pioneers studying thyroid metabolism in 1935 worked with iodine-128, but the short half-life of only 25 minutes was too short for their studies. They asked for a longer-lived iodine isotope, hopefully one with a half-life of around 7 days. In a remarkable response, the iodine-121 isotope with a half-life of 8 days, and otherwise roughly the same radiation characteristics as iodine-128, was quickly identified and made available for their research.

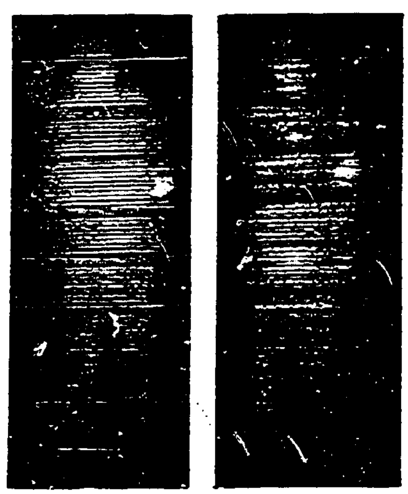
*For more information see Understanding the Atom booklets, *Radioisotopes in Industry*, *Food Preservation by Radiation*, and *Nondestructive Testing*.



Radioactive iridium was used to inspect the hull of the carrier, Independence.

An autoradiograph of a fern from Brazil in an area where the soil is naturally radioactive because of an unusually high concentration of radium-228.

Dental X ray



1 hr *48 hr*

Iodine-131 reveals spread of thyroid cancer in patient's body.

NUCLEAR RADIATIONS PENETRATE MATERIALS

All radiation applications work upon the principle that such radiations expend energy in materials they penetrate. The main effect is to jar electrons loose from atoms they hit, which produces positively charged ions. This *ionizing radiation*, if energetic enough, can also vibrate molecules apart into ions and into chemically reactive, fast-travelling, uncharged, molecular fragments, called *free radicals*. In this way the atom's nuclear energy is transferred from the atom and made available for different kinds of work, for example to power an electric generator for a space satellite,* or to serve in chemical combination with pharmaceuticals for body organ treatment.

*For more information see Understanding the Atom booklet, *Power from Radioisotopes*.

MEASURED IN TERMS OF ABSORBED DOSE *

The amount of energy absorbed per unit mass of *irradiated material* is called the *absorbed dose*, and is measured in units of *rems* and *rads*. A dose of one rad, abbreviation for *r*adiation *a*bsorbed *d*ose, means the absorption of 100 *ergs* of radiation energy per gram of absorbing material. (The erg† measures extremely small energy quantities; around 42 million ergs will raise the temperature of one gram of water only 1°C.) The rad is generally used for comparing non-biological effects of different radiation exposure doses. The rad cannot measure the extent of biological damage, since different forms of radiation cause different amounts of biological damage for the same amount of energy absorbed.

The *rem*, abbreviation for *r*adiation *e*quivalent *m*an, measures the extent of biological damage or change. A dose of one rem means the amount of dose of any ionizing radiation which produces the same *relative biological effect* (RBE) as one rad of absorbed dose of ordinary x-rays, gamma rays, or beta particles. This can be stated in an equation, and extended to cover neutrons and alphas,

$$\text{Dose in rem} = \text{dose in rad} \times \text{RBE}$$

In this equation the RBE's for the different radiation forms are shown below. They are merely experimentally determined factors that make the rem values turn out right in the equation.

Type of Radiation	rad	rem or RBE
X-rays and gamma rays	1	1
Beta particles	1	1
Fast neutrons	1	10
Thermal neutrons	1	4-5
Alpha particles	1	10-20

*For more information see Understanding the Atom booklets, *Your Body and Radiation*, and *The Genetic Effects of Radiation*.

†For more information see Understanding the Atom booklet, *Sourcebook on Atomic Energy*, Samuel Glasstone, D. Van Nostrand Co., Princeton, N. J., 1967, 883 pp., $15.00.

The RBE range, as indicated, for thermal neutrons and alpha particles takes into account that damage increases with particle energy. An increase in particle energy means the particle speed increases, and, as expected, the faster a particle travels the more damage caused when it smashes into soft tissue.

The roentgen, a third unit of exposure to ionizing radiation, abbreviated *r*, measures that amount of x-rays or gamma rays which will ionize 2,080,000,000 atoms in 1 cubic centimeter of dry air. This unit applies to no other radiation forms than x-rays and gamma rays and, strictly, to no other absorbing material than air. One *r*, however, is roughly equivalent to 1 rad of x-rays or gamma rays absorbed in soft tissue.

EFFECTS UPON THE HUMAN BODY

The effect of ionizing radiation upon human tissue can be beneficial, serious, or even lethal.* The damage happens because ionizing radiation splits body cell atoms and molecules into electrically charged particles and chemically reactive fragments. These body cell parts, made alien by radiation, are unable to function normally. They also create havoc when they react with normal cells.

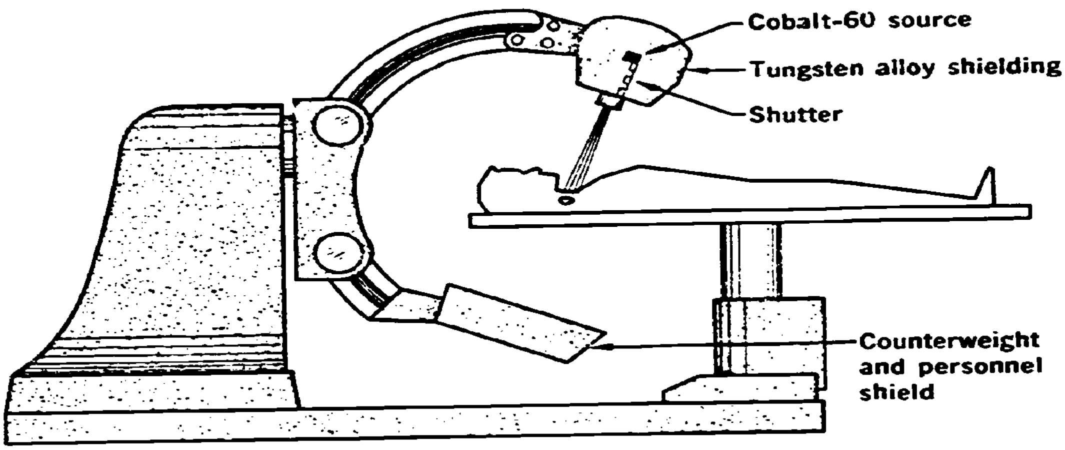
Biological damage from radiation increases as proportionately more of the body becomes exposed to the hazard. In medical treatments, such as cancer therapy, parts of the body often receive thousands of rads with no discomfort to the patient.† The patient would die if the same dose were applied to the whole body. A powerful tool such as ionizing radiation, like fire, must be handled carefully.

Radiation has the ability to stop cell division, a mechanism by which the body cells grow, hurting those cells which have rapid growth rates. Cells, in the outer skin layer, in intestine linings, and of the

*For more information see Understanding the Atom booklets, *Your Body and Radiation, The Genetic Effects of Radiation, The Natural Radiation Environment,* and *Atoms, Nature, and Man.*

†For more information see *Radioisotopes in Medicine,* an Understanding the Atom booklet.

blood, constantly die and must continually replenish themselves in vast numbers. Radiation will kill these healthy cells that are essential to life. But, this same energy often saves lives when directed as a versatile tool against the rapid-growing malignant cancer cells.



The symptoms of the human body with increased *whole body* radiation dose can be briefly summarized. Below 50 rad, no symptoms of body damage usually appear. From 50 to 100 rads there will likely be nausea and vomiting. Above 200 rad the more serious symptom of internal bleeding appears, from destruction of white blood cells and platelets. At around 500 rad, known as the LD50-30 dose, as defined, the average person who receives this dose in a short interval would die within 30 days.

No member of the U.S. public has ever received whole body doses of these magnitudes, and likely never will in view of the many safety precautions taken and the excellent safety record of the nuclear industry, as will be described later.

EXPOSURE SOURCES*

The average person in the United States today probably absorbs an average yearly radiation dose of about 0.3 rad. More than half of this comes from man-made sources, mainly from diagnostic x-rays. Only about 1/20 comes from the atmospheric nuclear weapons test fallout in

earlier years†—though some fallout isotopes are especially harmful because they resemble normal body elements in their chemical behavior. The 0.3 rad estimated total yearly dose falls well below the 5 rad yearly limit considered safe for workers whose jobs require they handle radioactive materials routinely.

The radiation dose received yearly, however, varies widely for each person because of the considerable difference in individual exposure to various existing man-made and natural sources. The lists below estimate typical doses from some of the man-made sources and typical yearly dose rates from some of the natural sources.

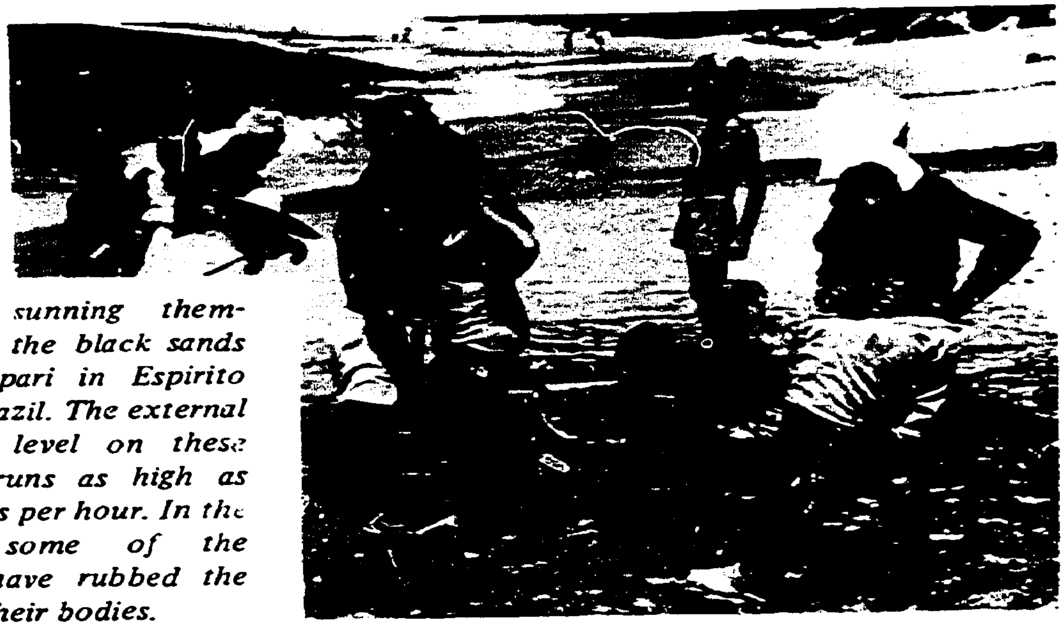
NON-OCCUPATIONAL ARTIFICIAL EXPOSURES

Source	Dose or Rate
Wrist watch dial, approx. 1 microgram of radium, gamma rays	1 mr/hr
Airplane instruments–pilot position	1 mr/hr
Shoe fitting (20 sec)	10 r
Diagnostic X ray	
14 X 17 chest plate	0.1 r
Photofluorographic chest	1 r
Extremities	0.5 r
G1 series (per plate)	1 r
Pregnancy	9 r
Fluoroscopy	15 r/min
Dental (per film)	0.5 r
Radiation Safety Guide for Population	0.5 r/yr.
Radiation Safety Guide for Radiation Worker	
Extremities	75 r/yr.
More sensitive body organs	5 r/yr.
Skin and thyroid	30 r/yr.

Add to these sources the internal exposure from other sources such as radioactivity occurring naturally, in well-water, ingested into the human body from radium leached out of the soil; and, relatively high concentrations of alpha-emitting elements in different foods, for example in Brazil nuts. Some beach sands contain the naturally

*For more information see Understanding the Atom booklet, *The Natural Radiation Environment.*

†For more information see Understanding the Atom booklets, *Fallout from Nuclear Tests* and *Atoms, Nature, and Man.*



Tourists sunning themselves on the black sands of Guarapari in Espirito Santo, Brazil. The external radiation level on these beaches runs as high as 5 millirads per hour. In the picture some of the bathers have rubbed the sand on their bodies.

radioactive element thorium which emits gamma rays and alpha particles. Some houses of brick or concrete, that contain high radium-bearing clays or limestone, irradiate their occupants at about three times the rate from a comparable-sized house of wood. As observed from these examples, the average yearly dose a person receives depends upon his habits, sex, occupation, and, the location and material of his house.

RELATIVE ALPHA ACTIVITY OF FOODS

Food Stuff	Relative Activity
Brazil nuts	1400
Cereals	60
Teas	40
Liver and kidney	15
Flours	14
Peanuts and peanut butter	12
Chocolates	8
Biscuits	2
Milks (evaporated)	1–2
Fish	1–2
Cheeses and eggs	0.9
Vegetables	0.7
Meats	0.5
Fruits	0.1

*NUCLEAR ENERGY RELEASED**

The whole subject of atomic energy rests upon Albert Einstein's mass-energy equation, $E = mc^2$, which first pointed to the possibility of releasing large amounts of the atom's energy by converting part of the atom's nuclear mass directly into energy. Mass and energy are two forms of the same thing, that is, mass can be changed directly into energy, and vice versa. As Einstein put it, "the mass of a body is a measure of its energy content." In his famous mass-energy equation, m is the mass equivalent of the energy E, related by the square of the speed of light, c, in a vacuum. ". . . things which are seen were not made of things which do appear."

This means, for example, that because of heat energy liberated in a coal fire, the ashes and gaseous products from the coal fire weigh less than the same unburned coal and the oxygen required for burning. Energy always has to be produced at the expense of a mass loss, and mass at the expense of energy. Einstein's idea startled scientists at the time because it was against their experience, even against two laws which they held to be fundamentally true beyond dispute.

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*For more information see *Our Atomic World*, an Understanding the Atom booklet, and *Basic Nuclear Physics*, Texas Atomic Energy Research Foundation, Fort Worth, Texas, Box 970, 76101, 1963, 43 pp.

These were the laws of conservation of matter and of energy. Matter can neither be created nor destroyed, only changed into another form of matter. In the same way energy was held to be conserved, and could only be changed into another form of energy. A more broad interpretation was needed of the two conservation principles. Actually, they are true only if taken together, that is, only the *combined* quantities of mass and energy are conserved.

The mass-energy effect in chemical reactions had not been detected before because the mass loss was always less than the most sensitive chemical balances were able to detect. To illustrate this, 100 grams of any substance taking part in a chemical reaction liberates about 1 million calories at most. According to Einstein's equation, if the appropriate values are substituted into the equation, a weight change, m, of only 0.00000004656 gram will result. This represents a weight loss less than 1 part in a billion, a change too small to detect.

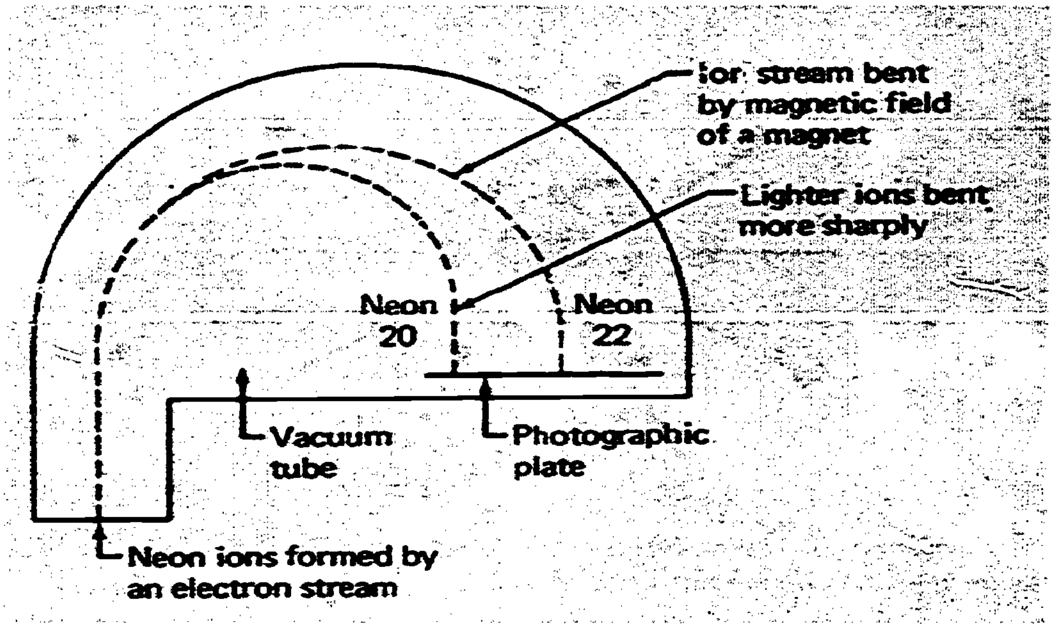
In nuclear reactions a much greater portion of the atom's mass can be changed into energy. This energy release from the atom's nucleus exceeds by several million times the maximum possible energy release for chemical reactions. Weight changes for nuclear reactions are therefore appreciable enough to be measured.

Man's faith in another universally held premise was shattered in 1920 when the *whole* of the atom was found to weigh less than the *sum of its parts*.* About this time the accuracy of the mass spectrometer† which experimentally measures the atom's mass was substantially improved. With this improved instrument the mass determined for any atom except hydrogen was, surprisingly, always less than the total weight that could be predicted by adding up the weights of the protons, neutrons, and electrons in the atom.

This apparent discrepancy indicates an equivalence between the atom's mass and its energy, which can be understood by reference to the conservation principle. Since some mass in the atom's nucleus disappeared and since mass cannot be destroyed, the mass must have been changed into energy. As described next, the mass which was lost became energy that holds the atom together.

*For more information see Understanding the Atom booklet, *Our Atomic World*.

†For more information see Understanding the Atom booklet, *Spectroscopy*.

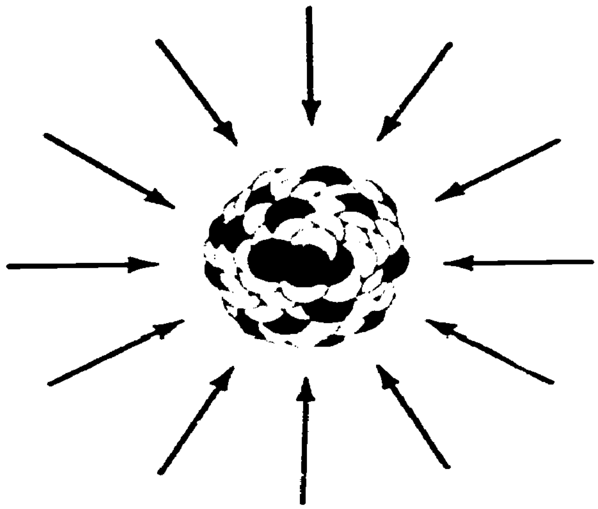


Mass spectrometer as used to measure the atomic weight of neon

TIES THAT BIND THE NUCLEUS

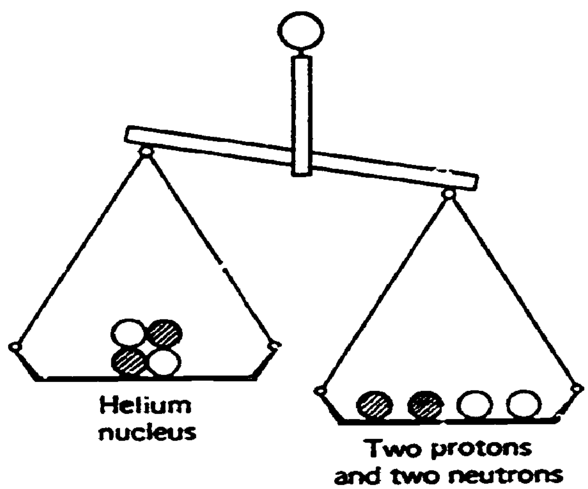
This energy, called *binding energy,** has been converted from mass in the atom's nucleus, and has been emitted from the atom when the neutrons and protons combined as a nucleus. Mass, as binding energy, has therefore been released and lost from the atom, by which sacrifice the nucleus particles became tightly bound together in a cohesive unit. This conversion of mass into energy has introduced a kind of internal stress into the nucleus that any outside force must overcome if the component protons and neutrons are ever to be separated. The protons and neutrons, now bound together in the atom's nucleus, can be separated only by resupplying their lost binding energy.

*For more information see *Basic Nuclear Physics,* Texas Atomic Energy Research Foundation, Fort Worth, Texas, Box 970, 76101, 1963, 43 pp.



The conversion of mass into energy has introduced a kind of internal stress that holds the nucleus together.

Consider, as an example, the nucleus of a helium atom with its 2 protons and 2 neutrons. A proton weighs 1.00812 amu, and a neutron 1.00893 amu, so from its parts a helium nucleus should weigh 2×1.00812 plus 2×1.00893, or 4.0341 amu, but a mass spectrograph shows it weighs only 4.0039 amu. The missing mass of 0.00302 amu, as Einstein postulated, must have been converted into binding energy.



A case where the whole is not equal to the sum of its parts. Two protons and two neutrons are distinctly heavier than a helium nucleus, which also consists of two protons and two neutrons. Energy makes up the difference.

The amount of this binding energy can be calculated from Einstein's equation, $E = mc^2$, by multiplying 0.00302 amu by the square of the speed of light. This small mass from a portion of one atom turned into energy in a *nuclear reaction* represents about seven million times more energy than could be obtained from the same atom in a *chemical reaction*. This energy would be released if 2 protons and 2 neutrons combined to form a helium nucleus. Conversely, this much energy must be supplied before the neutrons and protons in a helium nucleus can be separated.

UNLOCKING THE BOND

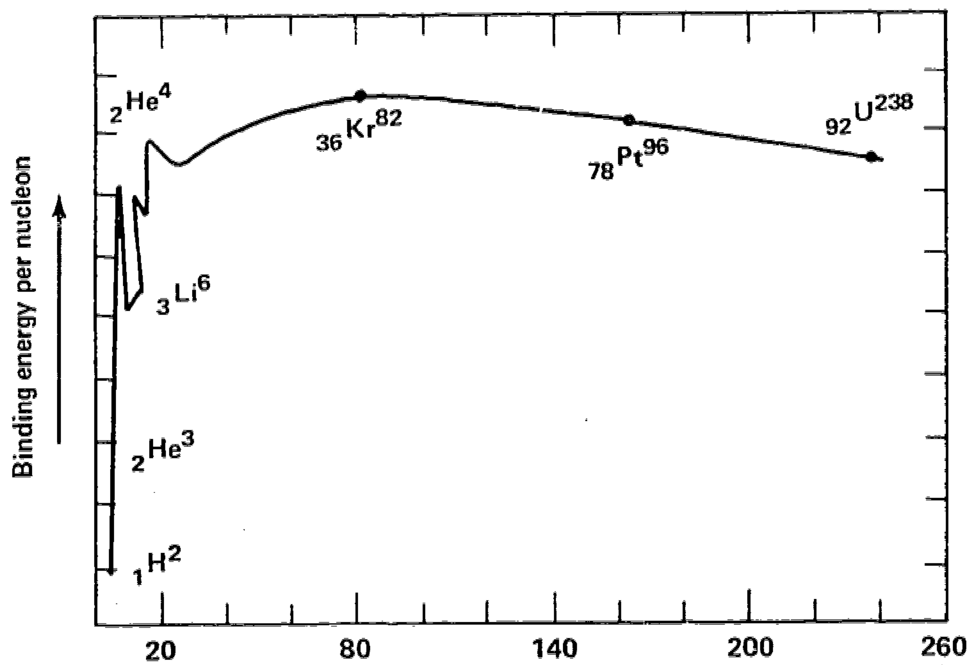
A way to turn matter into energy had yet to be found. Einstein had called attention only to the theoretical possibility when he showed the basic equivalence of energy and matter. Nature had to cooperate, so to speak, with one or more of the chemical elements or their isotopes with physical characteristics to permit this in a practical way. The concept of binding energy points the way.

An increase in binding energy must *always* be accompanied by a simultaneous release of nuclear energy. A net increase of binding energy means energy that comes from mass. This energy becomes released *when* the atom forms from its nuclear parts, whether these parts be protons and neutrons, or other atoms. Suppose the helium nucleus in the above example were built from 2 hydrogen nuclei, instead of, as previously, from separate protons and neutrons. Calculated as before, there would again be a net increase in binding energy (a decrease in mass) of the helium nucleus over the two hydrogen nuclei. This would result in a release of nuclear energy.

Each of the chemical elements can be similarly analyzed to see the possibilities in general of releasing this nuclear energy. Binding energies are calculated for each of the elements and their isotopes, as calculated here for helium. For each element the curve below plots binding energy per *nucleon*—total binding energy for each atom nucleus divided by that nucleus' total number of neutrons and protons—vs mass number. The curve can then be examined to see which particular reactions between nuclei would cause a binding energy increase per nucleon, that is, which reactions would release energy.

The curve shows that the binding energy per product nucleon increases, therefore energy will be released, for either of two general types of nuclear reactions:

in nuclear *fusion*, when heavy nuclei are built from light nuclei, or
in nuclear *fission*, when heavy nuclei are split into light nuclei.

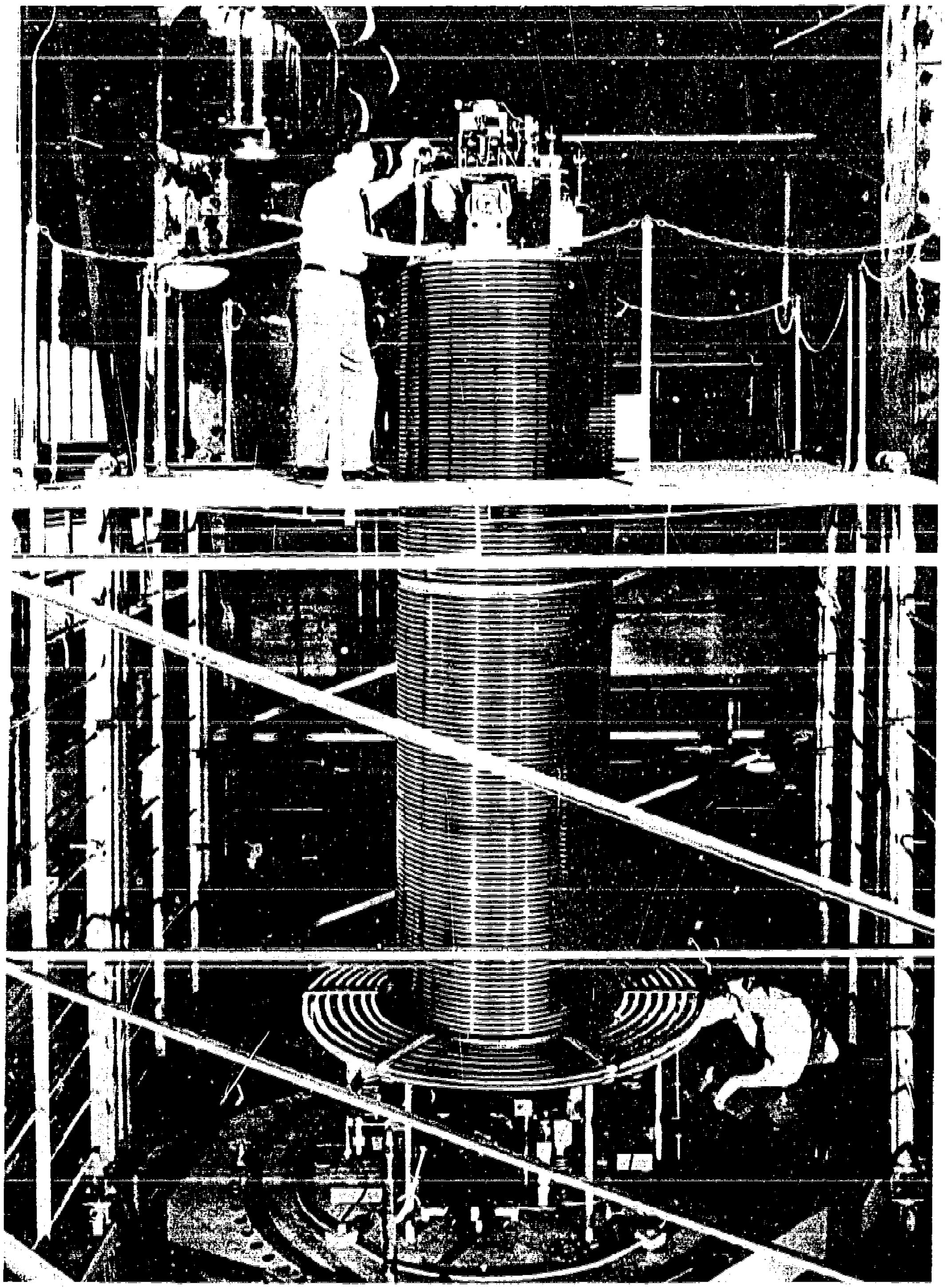


The variation of binding energy per nucleon with mass number

A fusion reaction, such as the fusion of hydrogen isotopes into helium, converts about 1 percent of the reacted mass into energy. The less energetic fission reaction, such as the fission of many of the heavier elements into small nuclei, converts about 0.1 percent of the reacted mass into energy.

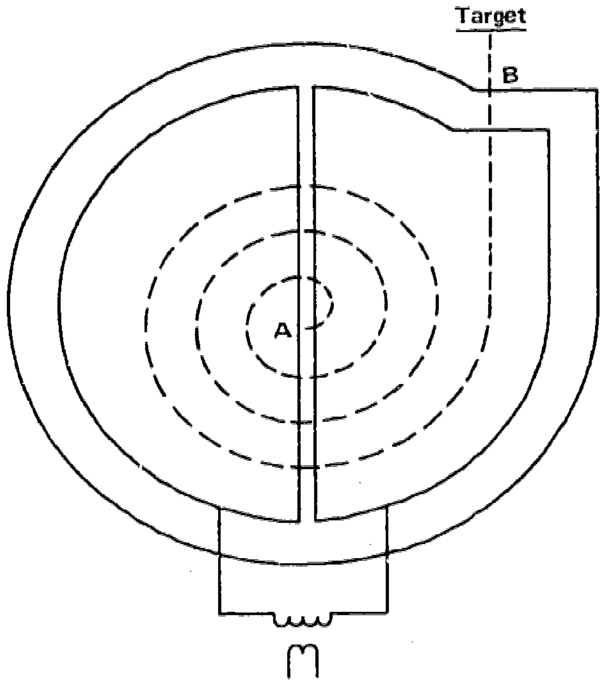
In the early 1930's machines for accelerating charged particles, accelerators* were developed. With these, physicists demonstrated nuclear reactions that released large amounts of energy, though at the expense of even greater amounts of energy. The neutron, discovered by Chadwick in 1932, was welcomed as the perfect bullet for these

*For more information see *Accelerators*, an Understanding the Atom booklet, and *Basic Nuclear Physics*, Texas Atomic Energy Research Foundation, Fort Worth, Texas, Box 970, 76101, 1963, 43 pp.



The very tiny world of the atom is invaded by very large tools such as particle accelerators, sometimes called "atom smashers."

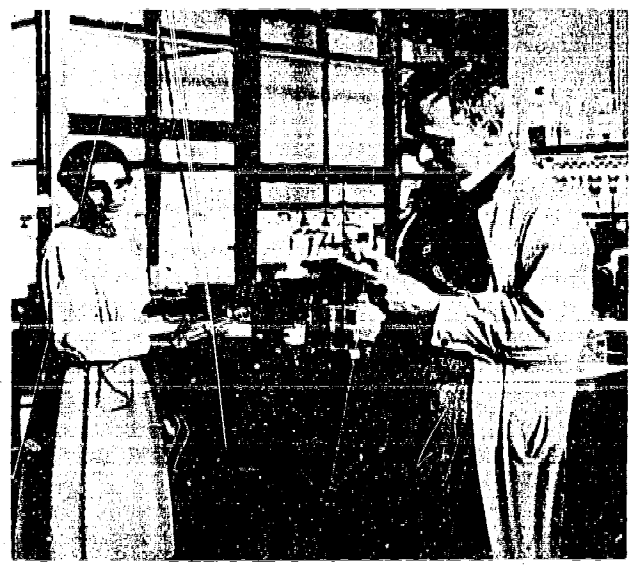
machines because it would not veer off from the positive nucleus like the alphas and protons, but would go straight into it. The neutrons are emitted when a suitable target material is bombarded with high-energy charged particles. A number of investigators, among them the Italian physicist, Enrico Fermi, irradiated many different isotopes with neutrons to see what would happen.



Simplified diagram of the cyclotron, a particular kind of accelerator. An ion formed at A will spiral outwardly around the dees many thousands of times before ejection through B with high energy.

Despite this active research, nuclear energy in the early 1930's was little more than a nebulous idea. Electrical power from nuclear energy was as remote a prospect then as the unlikely idea of cooling the ocean to extract heat for practical work, as E. O. Lawrence, an early nuclear pioneer, said in 1938. For any significant application these energetic nuclear reactions must be self-sustaining, capable of being controlled, and must release large amounts of energy. Researchers had no idea how to reach these goals. If nuclear energy could ever be harnessed, they vaguely felt this would be far into the future, perhaps around the turn of the century, and that success in fusion would likely succeed before fission. The outlook changed almost overnight because of a new discovery.

In 1939, two German chemists, Hahn and Strassman, and two physicists, Meitner and Frisch, in their work with neutron irradiation, discovered an isotope with totally unexpected and almost incredible characteristics. Uranium-235, which occurs in natural uranium in a 0.71 percent concentration with the more abundant uranium-238 isotope, was found to split, or *fission,* when struck by neutrons of any energy. More important, this long-lived isotope liberates new neutrons as it fissions, which permit a self-sustained nuclear reaction that generates energy continuously. No other natural isotope has these remarkable characteristics.



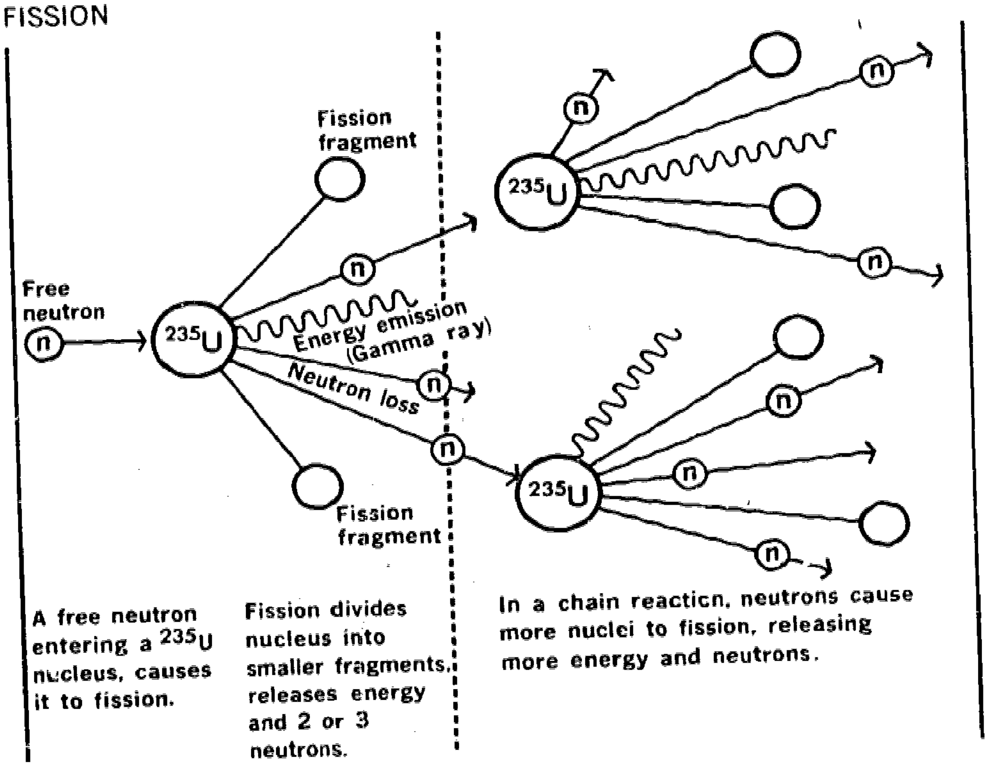
Lise Meitner and Otto Hahn in their laboratory in the 1930's

Courtesy, Gerald Holton and Duane H. D. Roller, *Foundations of Modern Physical Science,* 1958, Addison-Wesley, Reading, Mass.

Through this one unexpected discovery, which probably ranks in significance with the discovery of fire, the world has nuclear energy now, by fission, instead of possibly by the year 2000 through fusion, as the last generation anticipated. Uranium-235, or one of several other *fissile* isotopes which can only be produced from uranium-235 in nuclear reactors, must be present to a varying extent in the fuel of all nuclear reactors. Nuclear energy therefore proceeds directly from this isotope.

The story of nuclear energy therefore revolves around the nuclear fission reaction.

FISSION



If a free neutron enters a uranium-235 nucleus, the nucleus will divide, or fission, into two smaller atoms, releasing energy and 2 or 3 more neutrons. These neutrons can then go on to cause more uranium-235 nuclei to fission.

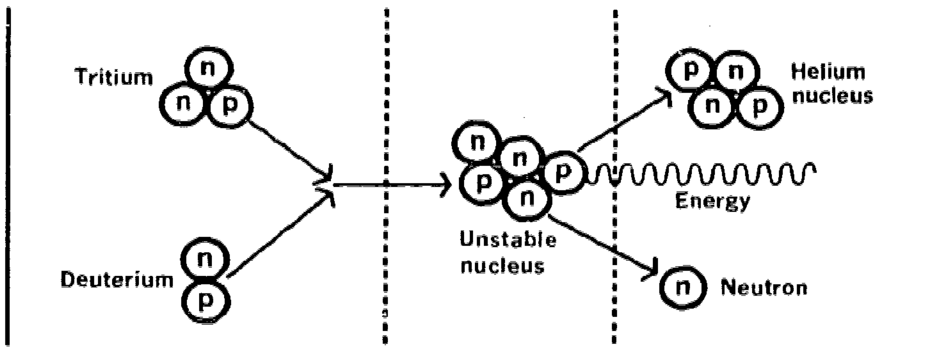
Significant problems remain to develop the sustained and controlled fusion reaction.* A controlled fusion reaction has yet to be initiated between light nuclei on a large enough scale to be sustained. These positively charged nuclei, usually of hydrogen, resist being brought close enough together to interact, so they have to be knocked together hard. Their speed of travel must be increased tremendously, so the gas must be heated to very high temperatures. In the so-called "hydrogen bomb" and in the contemplated peaceful uses of nuclear explosives,† a fission bomb furnishes the high temperature to trigger the uncontrolled hydrogen fusion interaction. Hydrogen nuclei will fuse in appreciable numbers only at temperatures of about 100 million degrees.

*For more information see Understanding the Atom booklet, *Controlled Nuclear Fusion.*

†For more information see Understanding the Atom booklet, *Plowshare.*

At these temperatures hydrogen becomes a completely ionized material, called a *plasma,* with a number of unusual properties including a notable instability. Any future success in controlled nuclear fusion depends upon confining a high-temperature and high-density instable plasma for at least milliseconds. So far, such a plasma has been confined for only microseconds. Studies of plasmas, directed toward the ultimate goal of controlled nuclear fusion, are proceeding in many parts of the world.

FUSION



When two isotopes of hydrogen, tritium and deuterium, combine or fuse, an unstable nucleus is formed. This releases a neutron and energy, forming a nucleus of helium.

This depicts the scene of December 2, 1942, when the first nuclear reactor achieved a self-sustaining chain reaction. The original painting, executed in 1957 by Gary Sheahan, Chicago Tribune Staff Artist, after 4 months of research, is now owned by the Chicago Historical Society.

NUCLEAR REACTORS*

Two kinds of events have largely advanced civilization's progress. First, there were the often unexpected discoveries as men searched to understand nature and the world around us. Of this kind was the discovery by Otto Hahn and Fritz Strassman of the remarkable uranium-235 isotope that fissions spontaneously to release tremendous reserves of the atom's nuclear energy. Second, there were the brilliant and largely engineering tasks which adapted these great discoveries into tools to benefit civilization. Of this kind was the first *nuclear reactor*, a controlled and sustained neutron chain reaction that utilized the uranium-235 discovery, by Enrico Fermi.

Fermi initiated this first neutron chain reaction on December 2, 1942 beneath the west stands of Stagg Field at the University of Chicago. This event is generally considered to have marked the beginning of the Nuclear Age.†

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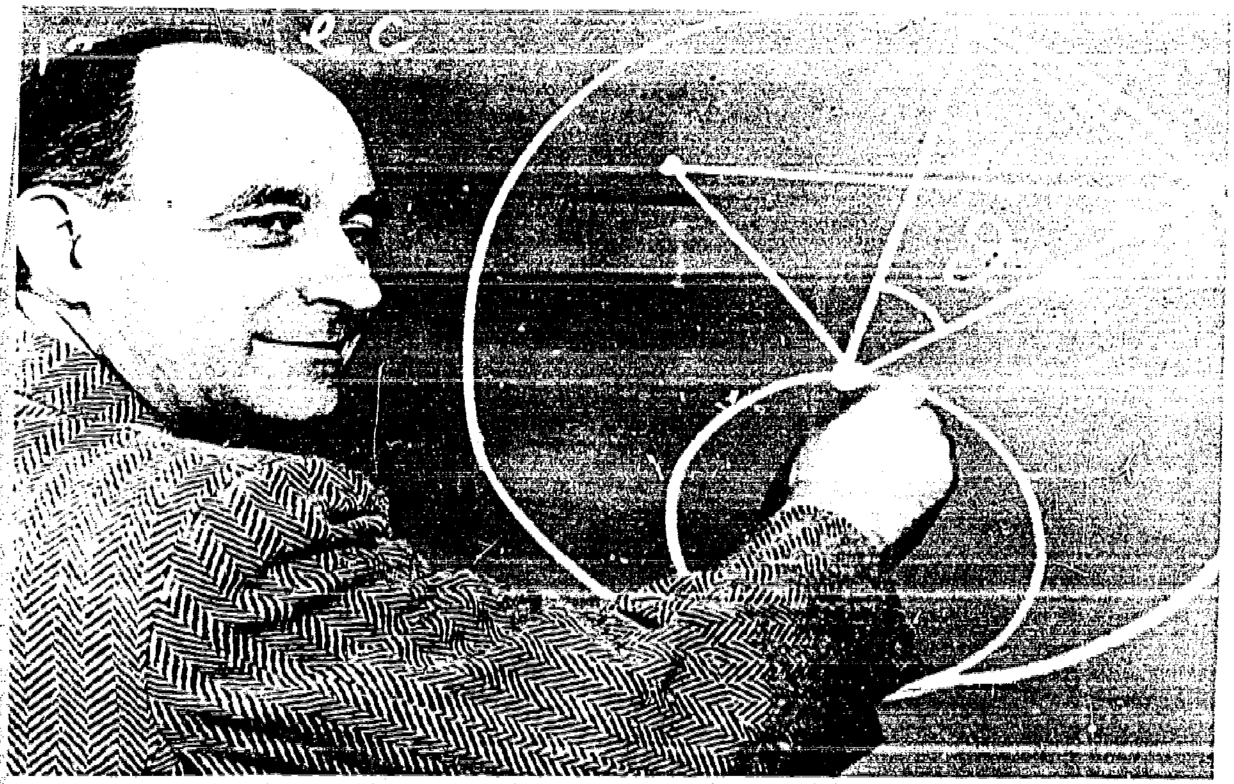
*For more information see Understanding the Atom booklets, *Nuclear Power Plants*, *Power Reactors in Small Packages*, and *Nuclear Reactors*.

†For more information see Understanding the Atom booklet, *The First Reactor*.



Enrico Fermi, the Italian physicist, led the team of scientists who built the first nuclear reactor.

FISSILE AND FISSIONABLE ELEMENTS*

Besides uranium-235, the two other commercially important *fissile* elements are uranium-233 and plutonium-239,† both *bred* in nuclear reactors when the *fertile* thorium-232 and uranium-238 atoms absorb neutrons. These two fertile elements are also *fissionable* elements—not *fissile*—in that they will fission, but only with high energy neutrons.

*For more information see Understanding the Atom booklet, *Sources of Nuclear Fuel.*

†For more information see Understanding the Atom booklet, *Plutonium.*

High energy neutrons are *fast neutrons.* This energy is of the kinetic kind, energy of motion. In a nuclear reactor, fast neutrons are born in fission and hurled from the exploding nucleus in random directions at a speed of about 10 miles per second. They must be *slowed down,* also called moderated or thermalized, to less than 2 miles per second before they can fission appreciable numbers of uranium-235 and uranium-233 nuclei. In a *fast reactor* the fissions occur mainly from fast neutron collisions with fissile nuclei, but in a *thermal reactor,* they occur mainly from slow neutron collisions.

While all three fissile elements will fission with neutrons of any energy, the uranium-233 and uranium-235 isotopes prefer fission with slow neutrons, and plutonium-239 prefers fast neutrons. But, the two fissionable elements, uranium-238 and thorium-232, will fission only with fast neutrons. Neutron speeds in the reactor must therefore be adjusted for the particular fissile element or combination of fissile and fissionable elements selected for a reactor. Obviously these factors considerably influence the nuclear reactor design.

Consider a typical fission neutron born in a reactor fueled with natural uranium—a mixture of one part uranium-235 to about 140 parts uranium-238—as was the Fermi reactor. Without any design to slow down the fast neutrons in the reactor, this neutron would probably become captured by a uranium-238 nucleus, if for no other reason than the relatively greater abundance of uranium-238.

The uranium-238 also has a better neutron absorptive ability for the high energy neutron. This competitive reaction can be overcome by a *moderator* material—an element with low mass number having little tendency to capture the neutron—placed adjacent to the fuel layers or rods. The usual moderators are ordinary water, heavy water, beryllium, carbon as graphite, and hydrocarbons. The neutron will then be gradually slowed by a series of rebounding collisions with successive moderator nuclei. If this moderated neutron then strikes a fissile nucleus, the odds are about 84 percent in favor of a fission.

A uranium-238 capture of this neutron would assist the neutron chain reaction, if the uranium-238 or the bred plutonium-239 fissioned. However, there is a chance that the neutron could be absorbed without fission. But, in any case the neutron chain reaction could not be maintained without the uranium-235 fission contribution. The fissile isotope is always the prolific and the necessary neutron producer in any reactor. The uranium-235 of this reactor must therefore be brought

into action before enough neutrons can be produced to maintain the neutron chain reaction. This particular fissile isotope prefers slow neutrons, which must obviously come from fast neutrons slowed down rapidly enough to prevent uranium-238 capture or other fission loss.

A neutron that smashes into a uranium-235 nucleus and fissions it will release several billion times more energy than the slow-moving neutron carried just before the fission. About 82 percent of the energy released by the fission comes from the kinetic energy of two or more fast travelling fission fragments. This energy becomes released in the reactor as heat. The heat from nuclear energy can substitute for the heat from a coal furnace which produces steam to generate electricity, or which distills saltwater from the oceans. The remaining energy of fission comes from gamma-rays, beta particles, neutrinos,* and neutrons. Each uranium-235 nucleus as it fissions emits, on an average, slightly more than 2 neutrons. The wave and particle emissions also benefit man in special ways, as described later.

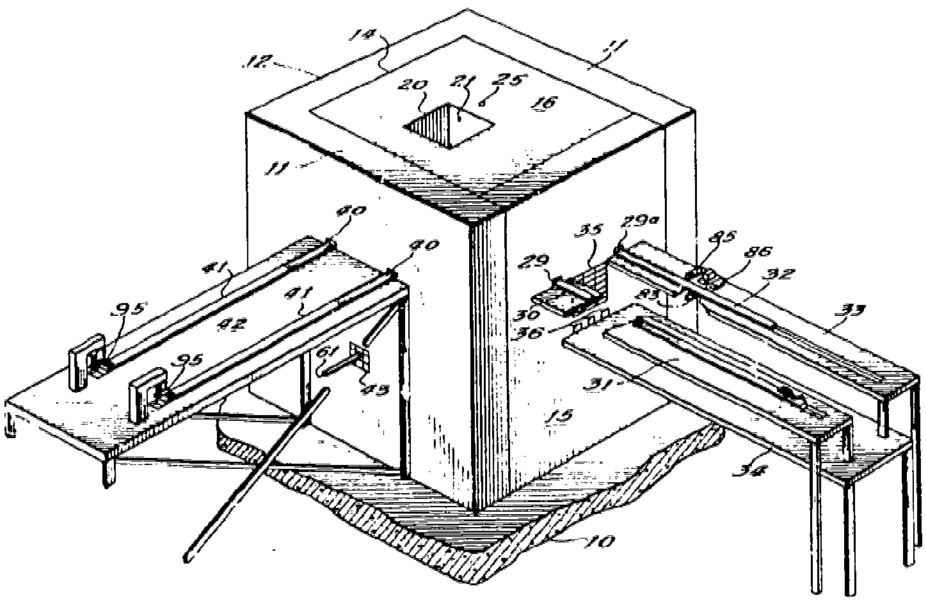
NEUTRON CHAIN REACTION

A single neutron, like a match that starts a fire, sets the neutron chain reaction going. Heat from the match starts the fire in only a small part of a combustible material. As this part burns, the temperature of adjacent parts are raised to the kindling point, and they burn. By this heat chain process the fire proceeds through the entire material, and continues until the chemical energy in the material has all been liberated. In fission the neutron chain reaction that liberates the atom's nuclear energy is similarly sustained and maintained by neutrons in a nuclear reactor.

For illustration, assume that each fission in uranium-235 yields exactly two neutrons. From the initial nucleus that fissions, the two neutrons emitted could fission two more uranium-235 nuclei and consequently release four more neutrons. These four neutrons could fission four other nuclei to release another eight neutrons, and these

*For more information see *The Elusive Neutrino*, an Understanding the Atom booklet.

eight neutrons could release sixteen neutrons, etc. The chain of reactions would thus continue and accelerate and the number of nuclei reacting would increase at a tremendous rate as in a combustion process.

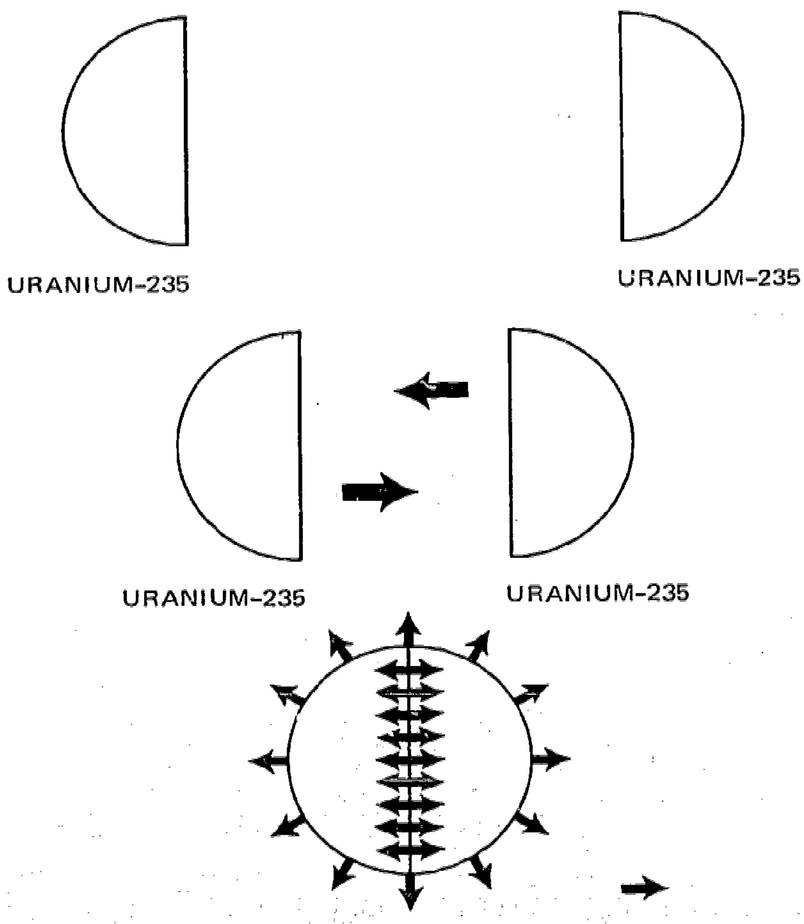


Patent No. 2,708,656 was issued on May 18, 1955 to Enrico Fermi and Leo Szilard. The invention it covers includes the first nuclear reactor, Chicago Pile No. 1 (CP-1). Although the patent was applied for in December 1944, it could not be issued until years later when all the secret information it contained was made public. This drawing was in the patent application.

Different events can prevent a neutron from causing fission. A uranium-235 or other fissile nucleus sometimes absorbs a neutron without fission. A neutron can also become lost to fission if absorbed in non-fissile nuclei such as in structural materials or fuel contaminants. Or, a neutron can escape by *leakage* from the fuel surface without becoming absorbed in anything. The smaller the fuel size the greater the chance that a neutron will become lost from the chain reaction by leakage. However, a neutron chain reaction will be sustained if an average of only one neutron per fission will in turn cause another uranium-235 nucleus to fission.

When just enough fissionable material is present to initiate a self-sustained chain reaction, the system is said to go *critical* and the amount of fuel is termed a *critical mass.* At this point the rate of

neutron gains from fission exactly equals the rate of neutron losses from the different leakage and other processes that remove neutrons. The critical mass depends also upon the kind of fissionable material, its concentration and purity, the material surrounding the assembly, and the geometry of the assembly.



Critical mass

The sphere has the smallest possible critical mass of any geometry. This bears some explanation. The neutron gains increase with fuel *volume* whereas the neutron losses by escape increase with fuel surface *area*. As the volume becomes larger there are more fissile nuclei, hence more fission neutrons are produced. A neutron born in fission on the fuel surface or close to the surface has a better chance of escape from the fuel mass without causing fission than if born deeper inside the fuel.

The relative number of neutrons that escape from a given fuel mass therefore decreases as the surface area—from which losses occur—decreases. For such a given fuel mass, equivalent to a set fuel volume, the sphere presents the smallest surface area for neutron escape. A critical mass in sphere shape would thus become sub-critical if reassembled into any other shape, that is, the self-sustained chain reaction would cease.

Neutron losses by leakage from the fuel surface can be reduced by a *reflector* around the fuel. A reflector bounces some of the neutrons that leave the surface back into the fuel so that they have opportunity to try again for fission with a fissile nuclei. The reflector reduces the critical mass size by reducing the leakage losses. Different reactors have different reflector materials.

STRUCTURAL COMPONENTS

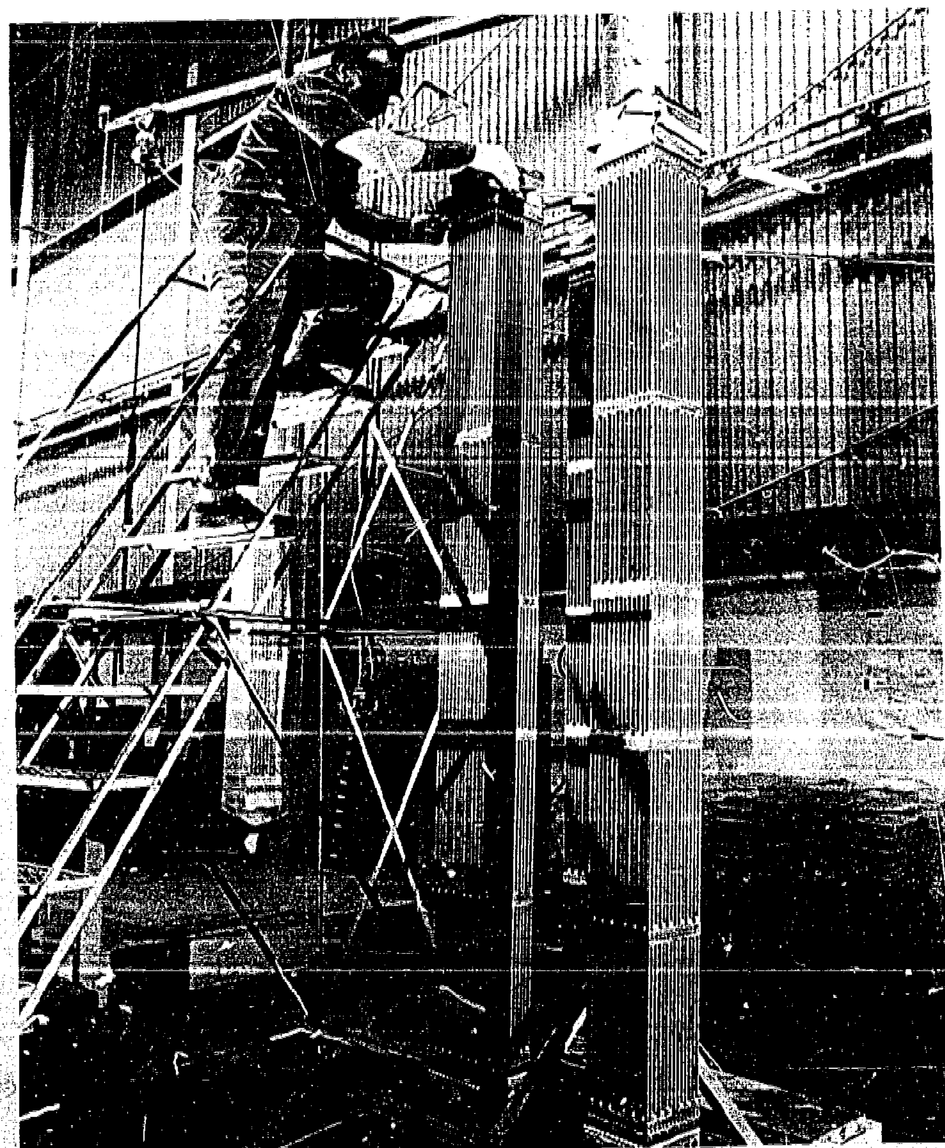
All reactors have a core in which the fission chain reaction proceeds, and in which most of the fission energy is released as heat. The core contains a nuclear fuel of fissile material, and often a fertile material. If most of the fissions are intended to result from slow neutrons, a moderator material must be interspersed throughout the fuel.

A neutron reflector surrounds the core, and can be the same material as the moderator. But, in a fast reactor, which can have no moderator, the reflector must be a dense element of high mass number to reflect neutrons back into the core without slowing them down.

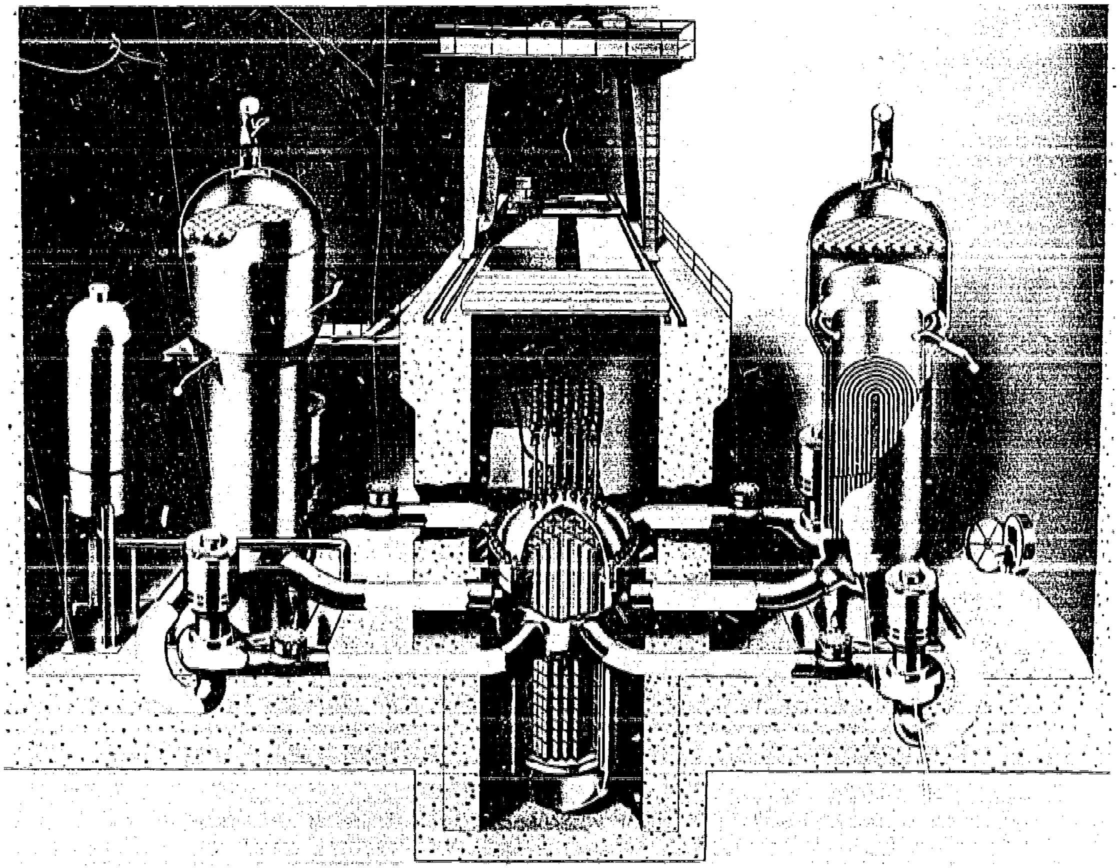
Heat must be removed from the reactor core by a circulating coolant such as water, liquid sodium, or gases such as air, carbon dioxide, or helium. If the reactor heat is to be converted into electrical power, the heat must be transferred from the coolant to a working fluid to produce steam or hot gas. This steam or hot gas would then drive a conventional turbine-generator. The fission heat in some reactors produces steam directly by boiling water within the reactor core.

The heat generated within the core varies directly with the neutron density, that is, with the number of neutrons per unit volume. Neutron density can be controlled in a given mass of fissile material by moving

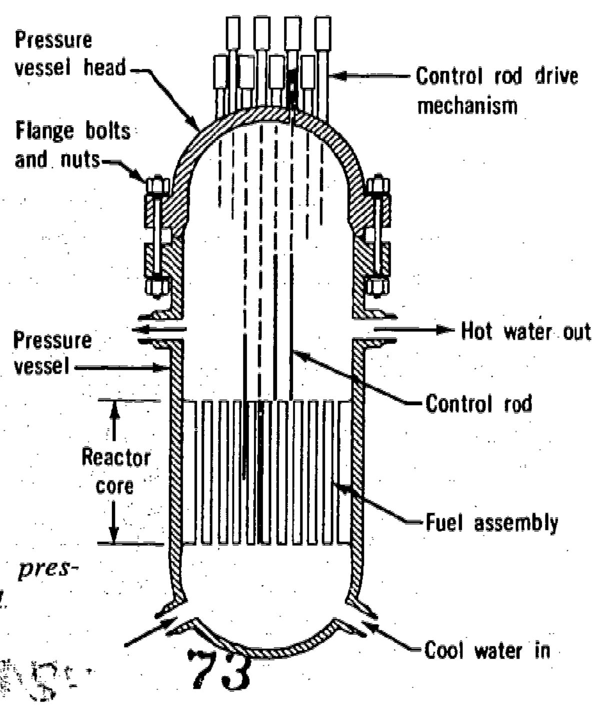
rods of neutron absorber material, like cadmium or boron, into or out of the core, which changes the neutron density. When fully inserted they will also stop the neutron chain reaction. Alternatively, a rod of fuel moved into or out of the core, or a portion of the reflector displaced, would have the same control effect.



Fuel element for civilian power reactor



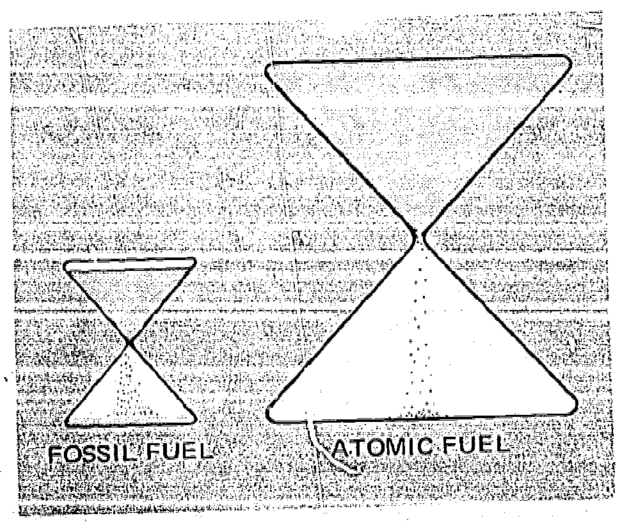
Cutaway view of a nuclear steam-supply system based on a pressurized-water reactor. Note size of man entering door at right.



Schematic view of the pressurized-water reactor vessel.

BREEDERS

The installed electrical power capacity throughout the world must generally double about every ten years due to population growth, and as living standards improve. This imposes such a drain upon the coal, oil, and gas fossil fuel reserves that some studies estimate we have only enough economical fossil fuel reserve for about 50 years. Fortunately, the economical supply of energy from nuclear fuels amounts to many hundred times that of the estimated fossil fuel reserves. This nuclear



A way of looking at our fuels situation

fuel reserve includes, mainly, the fertile isotopes uranium-238 and thorium-232, and, to a less extent, fissile uranium-235 of which the estimated abundance only slightly exceeds the fossil fuels. *Breeder* reactors must therefore be developed to exploit the predominant fertile proportion of these vast latent energy resources. Breeders—with fusion power further in the future—are indeed the only near-future possibility to supply the tremendous amounts of power that the world will need.

The neutrons in a *power breeder* perform two tasks. They produce power by fission and they breed fertile into fissile nuclei. The exciting possibility: *they produce more fissile material than they consume.* To perform both tasks there must be enough neutrons, and they must be efficiently employed. Each of the fissile isotopes, uranium-233, uranium-235, plutonium-239, and plutonium-241—which builds up in

power reactors after long-time neutron irradiation of plutonium-239—will produce more neutrons than the nuclear chain reaction needs. Consider, for example, a fissile plutonium-239 core with a fertile uranium-238 blanket around the core. To maintain the chain reaction, one neutron from each fission must cause another fission in the plutonium, which gradually becomes depleted as fission continues. But, if one additional neutron per fission could become absorbed in the uranium-238 blanket to produce a new plutonium-239 atom, the losses would exactly balance the gains. And, if more than one neutron per fission could become absorbed in the uranium-238 blanket, this would result in a breeding *gain*. Breeders thus offer the chance to increase the total amount of fissile material, as bred from fertile material, while they simultaneously produce energy to generate electrical power.

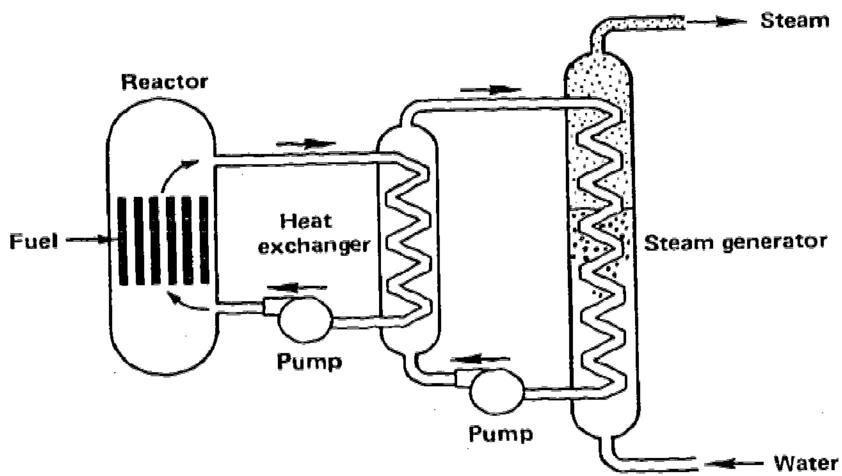
A fast neutron and liquid-metal cooled reactor offers one of the best chances for a breeding gain with plutonium-239 and plutonium-

There are two basic breeder "fuel cycles":

FISSIONABLE MATERIAL FED	FERTILE MATERIAL	FISSIONABLE MATERIAL FORMED
Plutonium-239	Uranium-238	Plutonium-239
Uranium-233	Thorium	Uranium-233

241 fissile material. The U.S. Atomic Energy Commission* (AEC) has a broad program underway to design and develop this type of reactor. Fission at the fast neutron speeds allows the fertile nuclei to compete for neutrons that would, at slow neutron speeds, mostly become absorbed by these particular fuel nuclei. In a thermal (slow neutron) reactor, less than one slow neutron per fission would be available for converting fertile into fissile nuclei with these fuel nuclei. On the other hand, thermal reactors are the indicated choice with a uranium-233 and thorium-232 breeder system, because of the different behavior of these isotopes, as previously described.

*For more information see *USAEC—What It Is, What It Does,* an Understanding the Atom booklet.



Nuclear steam-supply components in a liquid-metal-cooled breeder reactor

Many other reactor types exist and are being built. The booklets referenced at the beginning of this section describe the more important kinds in some detail, including the liquid metal-cooled breeder in which the breeding principle has been demonstrated. Most of the reactors being built to generate electricity in the United States today are of the water-cooled thermal type. These have already produced power at prices competitive to coal, witness the fact that since 1966 approximately half of all the total new electric generating capacity announced by the private industry utility companies in the United States has been nuclear.

SAFETY

Nuclear reactor safety,* aside from some ordinary industrial hazards, centers around precautions to contain the reactor's radioactive fission product wastes.† These are the ashes of the atomic furnace. The

*For more information see Understanding the Atom booklet, *Atomic Power Safety.*

†For more information see Understanding the Atom booklet, *Radioactive Wastes.*

vast majority, 99.99 percent by weight, of all fission products remain confined behind stainless steel or zirconium metal cladding of the typical tubular fuel elements,‡ until they are finally separated from the unused fuel and permanently stored.

Reactors need refueling only about once every year, and often less frequently. At refueling, the reactor is shut down, the top of the reactor vessel removed, and the spent fuel elements taken by crane to underwater storage. After several months the fuel elements have lost their short-lived radioactivity which includes most of the radioactive gases. They are then loaded into ruggedly-built, lead-shielded, steel containers and shipped to a chemical reprocessing plant for recovery of the unused fuel. Here, the fission products are removed, concentrated, and stored. Thus all except a small fraction of the fission products of an atomic reactor remain with the fuel and leave the reactor area with the spent fuel.

The primary coolant picks up the remaining 0.01 percent of fission products as it continuously circulates past the reactor's fuel elements to remove the heat load. These are mainly the gaseous and more easily vaporized fission product wastes that creep through minute imperfections in the fuel element cladding. The coolant fluid also accumulates neutron activation products, mainly from short-lived water activation products.

The primary coolant fluid circulates in a closed path, through the reactor core to pick up the fission heat, through a heat exchanger to transfer this heat load to a second *working* fluid, and back through the reactor. Instead of a water coolant, another type reactor uses high temperature steam that loses heat and condenses when flashed through a steam turbine to turn an electric generator. The coolants' radioactive contamination, always flowing in closed loops, remains contained within the reactor environs.

A small stream of the primary coolant is continuously bled off, separated of radioactivity, and returned to the system. This maintains the radioactivity below a specified maximum level. In the separation—by evaporators, demineralizers, filters, and the like—all but a small fraction of the radioactivity collects as waste concentrates and must be temporarily stored before final disposal. The remainder,

‡For more information see Understanding the Atom booklet, *Atomic Fuel*.

averaging a few millionths of a gram per day during normal operation, would normally be discharged as a waste stream so feebly radioactive that it generally meets drinking water standards. The waste stream then becomes further diluted when dispersed to the water that serves the reactor plant.

The small amounts of radioactive gases in the coolant exit through a tall chimney on a controlled basis to assure atmospheric dilution that meets strict regulations. These regulations are based upon the probable annual radiation exposure received by persons who live at the plant's outer boundaries.

Radiation levels throughout the plant and in the area, especially at the plant and area boundaries, are continuously monitored to assure safety.

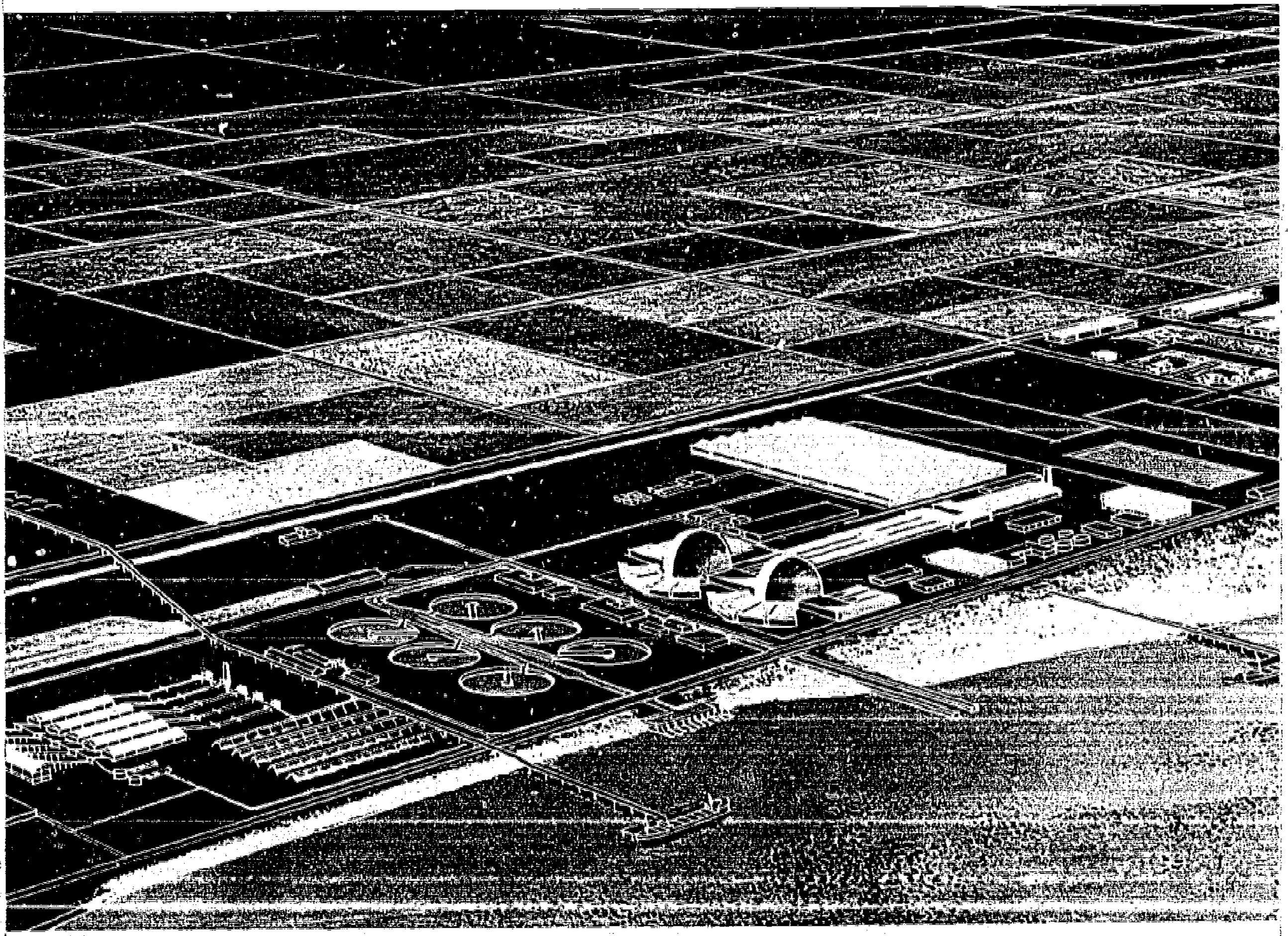
Every atomic power plant must obtain a construction permit and then an operating license from the USAEC. The applicant must satisfy AEC that the proposed plant will be built and operated safely. Furthermore, all the operations are subject to AEC inspection and compliance procedures.

A number of general safety criteria must be closely followed to emphasize safety in all the phases of power plant design, construction, and operation. The site selected must be such that in normal operation the radioactivity released will not contaminate air or potable water to levels that exceed the established guides. All parts of the power plant system must be designed to minimize accidents, either from human or mechanical failure, and to deal with the consequences of any credible accident. Operations and maintenance must be carefully planned with written and required procedures. Precautions must be taken, in event of an accidental release of fission products, to prevent radioactivity to surrounding areas. The reactor designer must consider all the different accidents that could happen and show that they would not represent any significant danger to the public.

The designer of a water-cooled reactor, for example, must consider the possibility of a loss of the core cooling water through a major break in the coolant piping connected to, but outside of, the reactor pressure vessel. Should this unlikely event ever happen, the following sequence of additional failures can be postulated: The nuclear fuel could overheat and melt through the fuel cladding. The cooling water released through the piping break would flash to steam. And, gross amounts of radioactive fission products could be carried by the escaping steam

through the break in the piping. The engineered safeguard answer is often to completely enclose the reactor and exterior piping with a prominent reactor containment shell, usually half-spherical in shape. Several kinds of pressure suppression systems, another type of containment, have also been designed to meet this unlikely event.

The nuclear industry has an outstanding safety record, because of these and other safety precautions. No member of the public has ever been injured by a nuclear accident at a central station power plant in the more than 20-years that nuclear power plants have operated. The disabling injuries among the industry's employees, from the most recent figures, amount to only about one-fifth the U. S. overall industrial average. This good record must be attributed in part to a vigorous AEC-sponsored program of safety research and tests. And, the utility industry is basically motivated to secure reliable service without plant shutdowns. To demand this, they have traditionally emphasized conservative design, selected dependable equipment, and required safe plant operation.



In an agro-industrial complex, as envisioned in this artist's conception, the heat from large nuclear reactors would desalt water for agriculture and generate electricity for industry.

AT MAN'S SERVICE

The nuclear energy field exemplifies the growing ability of technology to provide an abundance of the good things of life. Nuclear technology serves this purpose already in many and varied ways. Other greater services of the atom lie within technological reach. Of all these, the atom's ability to generate electrical power benefits man the most widely, now and in prospect for the near-future.

Consider the startling effect of low-cost unlimited supplies of power, upon our industrial economy and subsequently upon our society. Cheap unlimited power can supply basic human needs. The main ingredients can all be found in the rocks, the air, and seawater to generate unlimited supplies of energy and, with this energy, to produce fertilizer, freshwater, and other necessities. Energy will increasingly substitute for material resources as power costs drop. Lower grade ores

can be economically processed. New industrial processes become economically feasible. Waste products can b   processed into usable chemical forms, or at least into products that would not pollute the environment. An abundance of low-cost material goods would permit some desperately needed social and economic, as well as ecological, progress. The beneficial impact would be profound, beyond any effect from technology that has yet been experienced, even in the developed nations. The agro-industrial complex, mentioned below, could possibly alleviate material want and deprivation altogether as the major cause of human suffering.

This section mentions some of the atom's benefits. The reader should see the references for a more complete picture.

NUCLEAR-ELECTRIC POWER*

The atom has the ability to generate electricity in large amounts without adding to the burden of air pollution.† Nuclear power stations now supply electrical power around the world. The United States alone has 98 nuclear power plants either in operation or planned. By 1980 roughly one-quarter of the total electrical generating capacity will be nuclear, based upon the rate of nuclear plant growth to date. By the year 2000, probably all the new power plants in the United States will be nuclear.

Only nuclear and fossil fuels, of all the possible energy sources, exist in quantity enough to supply the large blocks of energy that the world needs to generate electrical power economically today. But, the economic reserves of fossil fuels are limited, and in view of the increasing consumption, may not last much beyond another generation. The world demand for electrical power has historically doubled about every ten years. Only the nuclear fuel reserves, much more abundant than the fossil reserves, will be ample to generate electrical power economically in the future.

*For more information see Understanding the Atom booklet, *Nuclear Power Plants.*

†For more information see Understanding the Atom booklet, *Nuclear Power and the Environment.*

The cost of nuclear-generated electricity falls rapidly, more rapidly than for fossil-generated electricity, as the size of the generating plant increases. This *scale-up* advantage, and the plentiful resources of nuclear fuel when the breeder reactor will have been commercially developed, point to an abundance of low-cost energy for the foreseeable future.

NUCLEAR DESALTING‡

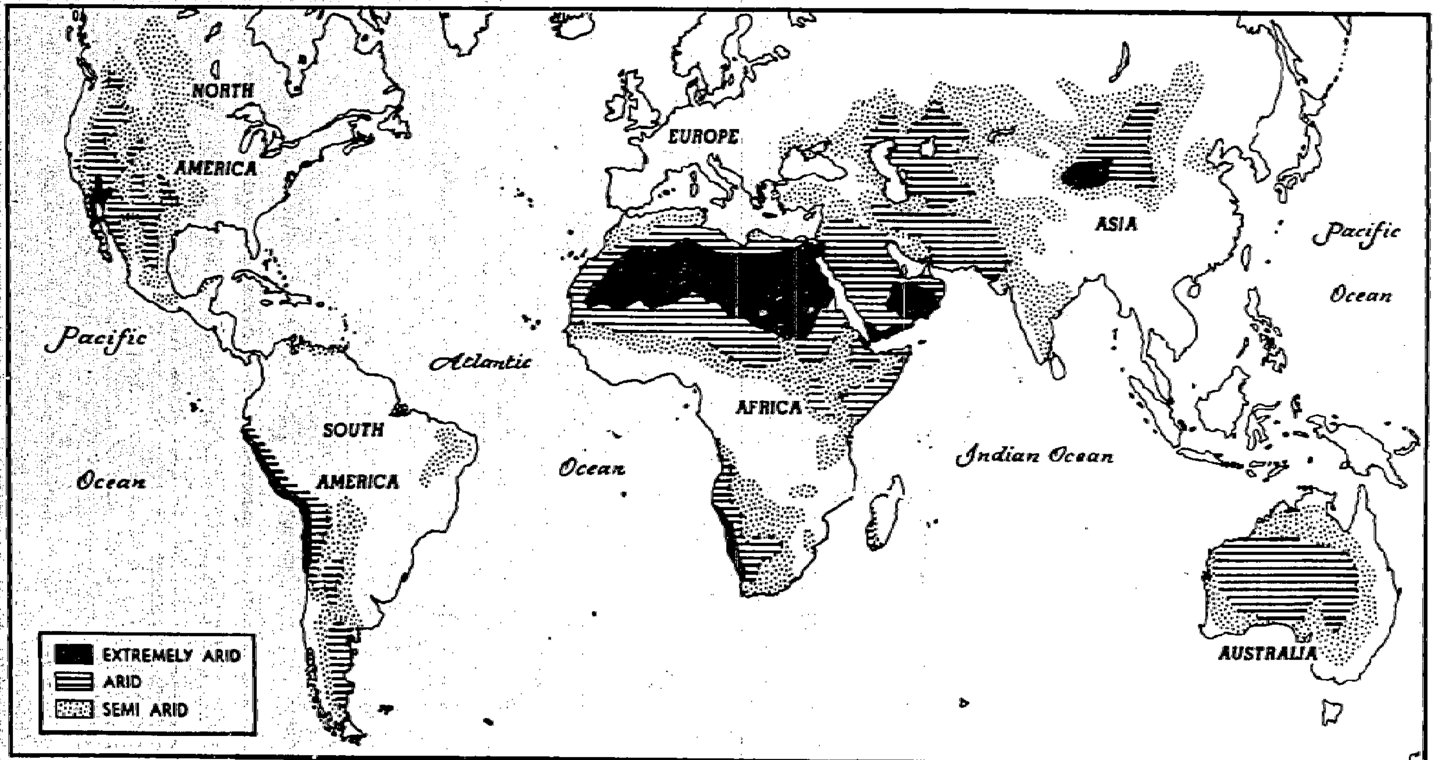
One plan for use of this energy has stirred imaginations and lifted hopes all over the world; apply atomic energy's almost limitless power to turn saltwater from the oceans into pure water. Desalting technology is being developed, and abundant pure water is within reach. The search for new water sources is spurred by a rapidly expanding world population, which almost certainly will have doubled by the year 2000. Yet even today the available freshwater resources limit the food supplies that can be grown.

AGRO-INDUSTRIAL ENERGY CENTER COMPLEX

The nuclear desalting technology leads to the agro-industrial energy center complex. The complex would combine a variety of energy-consuming industrial processes, a large modern agricultural farm, and a large desalting plant to irrigate the farm. New acreages of the thirsty coastal deserts, several hundred thousand acres for each complex, would be brought into intensive cultivation via nuclear desalinated seawater. The industries, with cheap energy, would create basic and finished goods from low-grade raw material resources that are widely spread over the world. The complex could turn the wonders of science into man's service to produce most of his material wants. It offers a

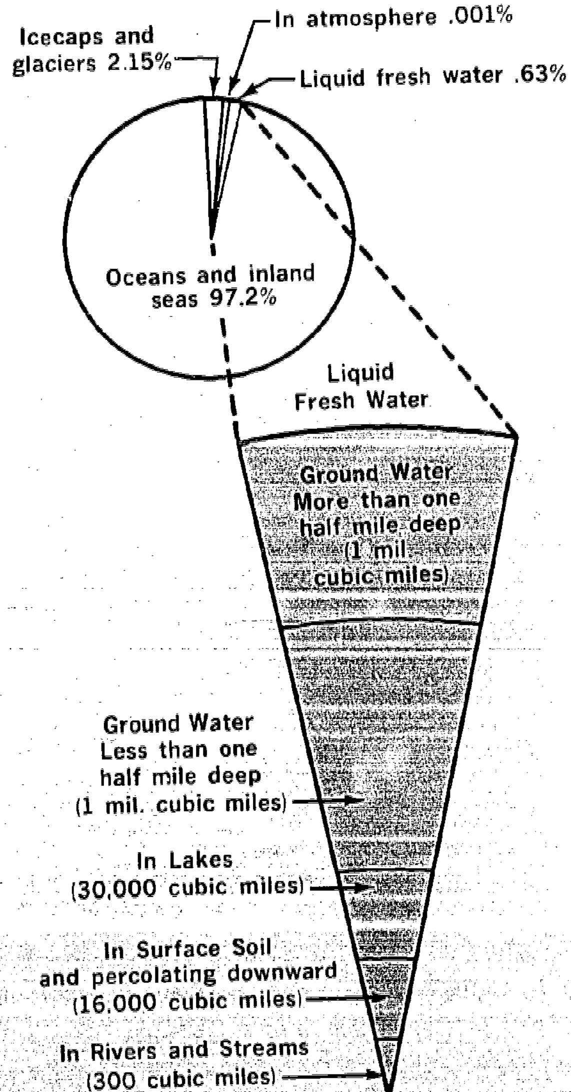
‡For more information see *Nuclear Energy for Desalting*, an Understanding the Atom booklet.

ARID REGIONS OF THE WORLD



As the world population grows and more lands become industrialized, the demand for fresh water soars. Arid regions, shown on the map, are becoming increasingly populated. In those designated "extremely arid" there are periods of a year or more in which no rain falls.

THE WORLD'S WATER

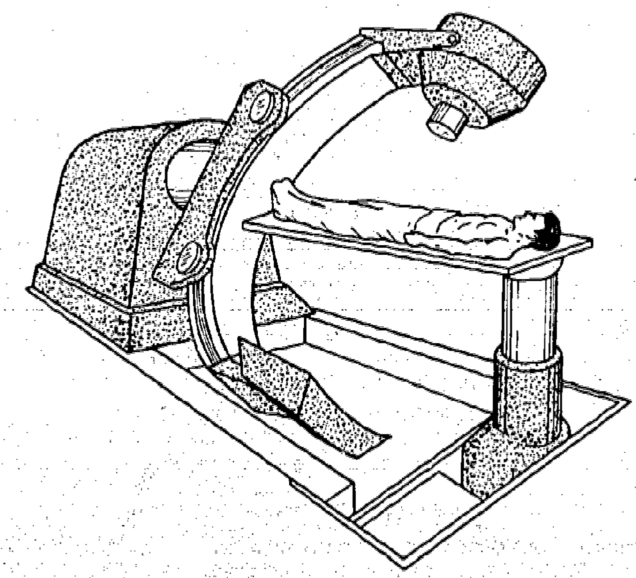


Most of the world's water, as shown in this diagram, is in the oceans or the ice sheet covering Antarctica. Most of the water on land is underground. The percentage readily accessible in lakes is small.

short but arduous route whereby the technology of the developed nations, from which they gain their high standards of living, can be transplanted to the developing nations.

MEDICINE*

Few people realize the considerable extent to which the atom has influenced modern medicine. Every day, the atom in medicine, often in intimate contact with man, saves human lives and relieves human suffering. The tools of nuclear medicine are mainly some 30 radioisotopes. These are employed flexibly in many tests and procedures to take different kinds of advantages of the radioisotopes' radiation energy. Radiation destroys malignant cancer tissue or suppresses certain

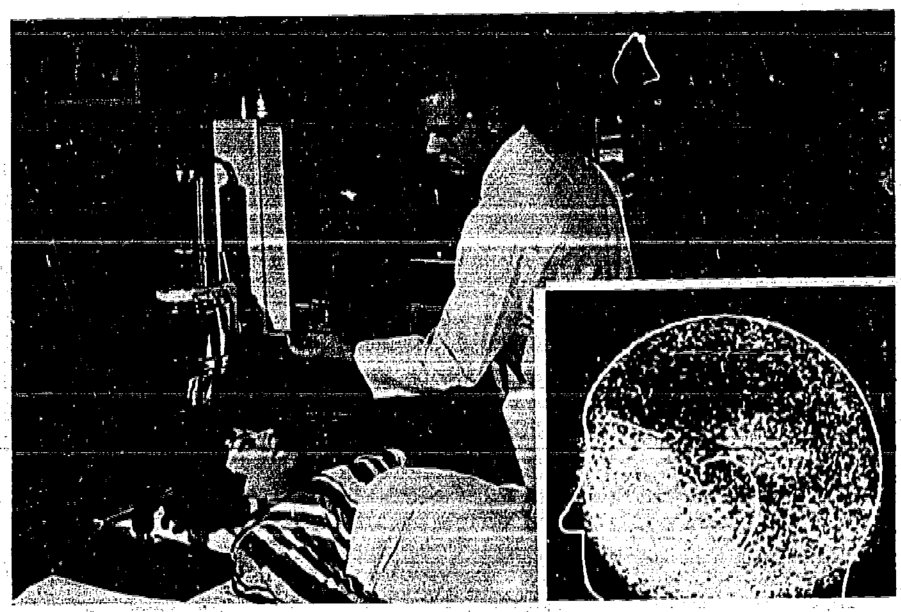


over-active body functions. Long-lived radioisotopic power sources are being designed to replace batteries in surgically implanted prosthetic devices, such as the heart pace-maker. And, in their widest role, radioisotopes serve as tags or labels to identify natural compounds in the body, for diagnoses of disease and to measure specific body organ functions; to explain:

Different short-lived radioisotopes are administered, for various diagnoses or tests, as medicinal doses in minute amounts. They become part of living cells or tissues, and are thoroughly mixed with and chemically identical to their much more numerous, otherwise alike,

*For more information see Understanding the Atom booklets, *Radioisotopes in Medicine* and *Radioisotopes and Life Processes.*

stable isotope counterparts in the same kinds of body organ cells or tissues. These *tracer* radioisotopes emit signals that travel through space like radio signals. Like the sound from the bellwether leader of a flock of sheep, their signals serve to trace and monitor organ function because these signals transmit information that can be received outside the body and precisely measured by various kinds of counting and recording instruments. These signals are more precisely identifiable than



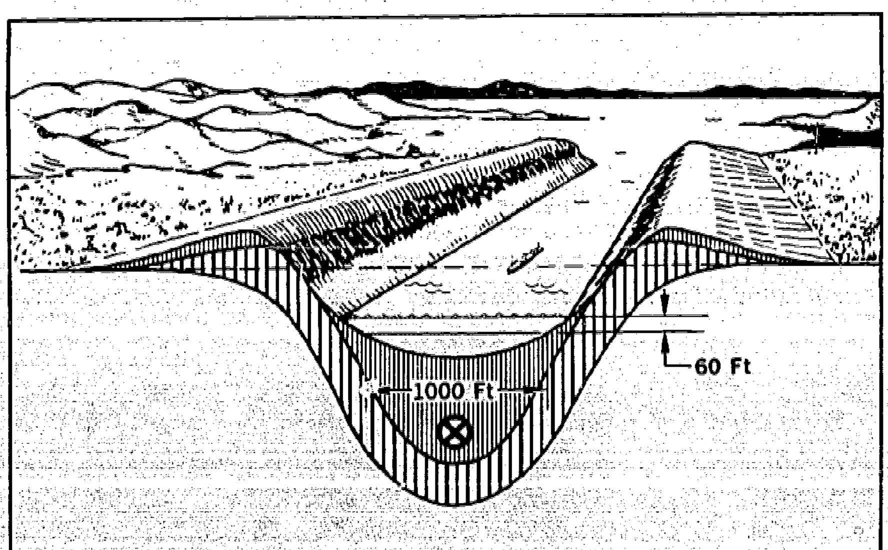
The inset picture of a brain scan shows a tumor, indicated by light area above ear. (Light area in facial region is caused by uptake in bone and extracellular space.) The photograph shows a patient, completely comfortable, receiving a brain scan on one of the three rectilinear scanning devices in the nuclear medicine laboratory of a hospital.

A linear photoscanner produced these pictures of (A) a normal thyroid, (B) an enlarged thyroid, and (C) a cancerous thyroid.

fingerprints in crime detection. They announce which isotope is present, how much, and where located. By means of radioisotope labelling coupled with different tests and procedures, many diseases can be diagnosed and different body organ functions can be measured. For example, thyroid, pancreas, and kidney diseases and malfunctions can be identified, brain tumors can be diagnosed, blood volume measured, and many others.

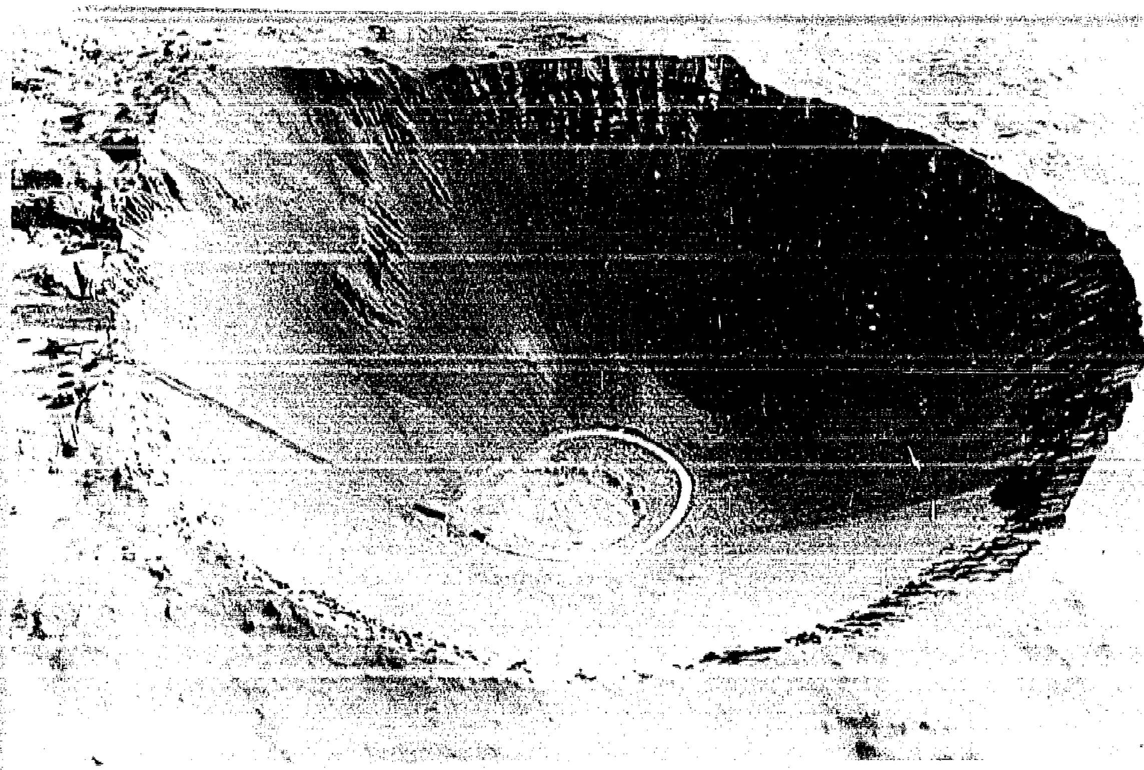
NUCLEAR EXPLOSIVES*

There has been considerable success recently in experimental research to adapt the vast energy from nuclear explosives for gargantuan-sized peaceful projects. Nuclear explosives detonated below the earth's surface can simultaneously break and move tremendous quantities of earth. Based upon this technique, ways are being studied to dig sea level canals between oceans, to cut highway and railway



A sea-level canal, dug by nuclear explosives, as shown in this cross-section drawing, would be 1000 feet wide and at least 60 feet deep.

*For more information see *Plowshare,* an Understanding the Atom booklet.



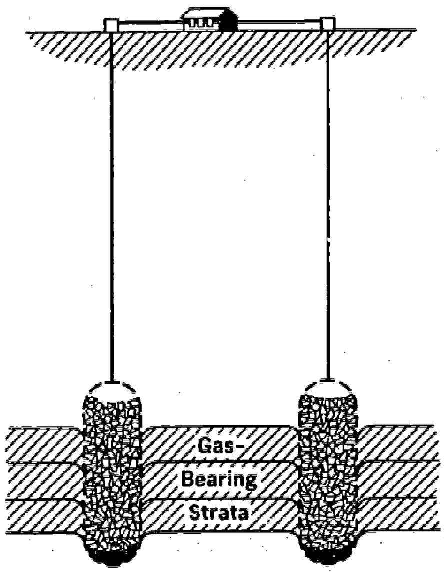
The 100-kiloton SEDAN event formed the largest excavation ever produced by a single man-made explosion. Note the size of automobiles and structures near the crater rim.

passes through mountains, and to create harbors and lakes where none existed before. The use of nuclear explosives to construct a new Panama Canal wider and deeper than the old lock canal is under consideration.

Underground, nuclear explosives have demonstrated a potential to help recover natural resources. Poorly-productive natural gas wells have been stimulated into accelerated production. Plans are underway to fracture oil shale for subsequent in-place retorting, and to prepare ore bodies for in-place leaching. Underground storage areas could likewise be formed to hold natural gas or dispose of wastes.

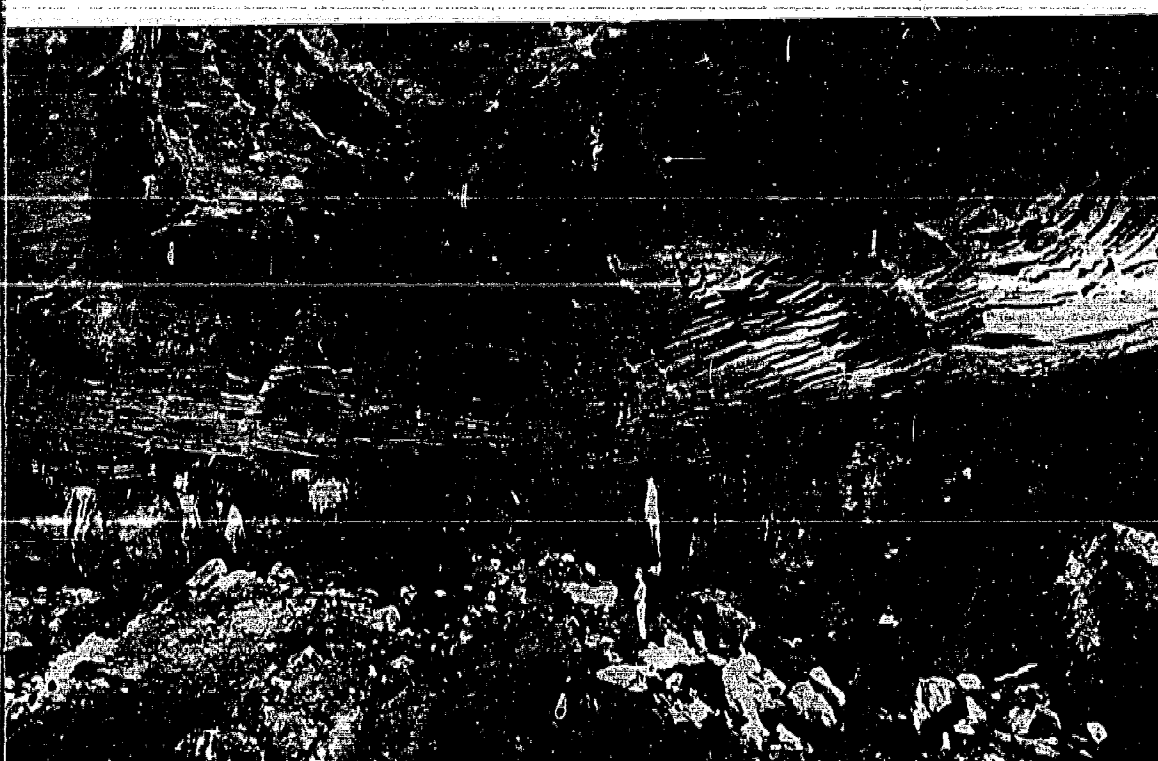
In Project Rulison in September 1969, 45 miles northeast of Grand Junction, Colorado, a nuclear explosive equivalent to 40,000 tons of TNT was detonated 8,430 feet underground to stimulate gas recovery in an underground reservoir. In 1967 a similar experimental shot in New Mexico, called Project Gasbuggy, first demonstrated that gas production of an underground reservoir could be improved in such a way. In the next 20 years, the gas recovery at both locations should increase several fold over what would have been otherwise possible.

.......And the thermonuclear explosive for the SEDAN shot, shown being lowered into the drill hole.



A chimney of highly fractured, permeable material created by a nuclear explosion may increase the productivity of natural gas fields in which the gas does not flow freely. The nuclear explosion would produce a large "well" in which gas could collect and then be pumped to the surface.

Nuclear explosives come in more compact and lighter weight packages than chemical explosives because they are considerably more powerful. A nuclear explosive equivalent to 2 million pounds of TNT

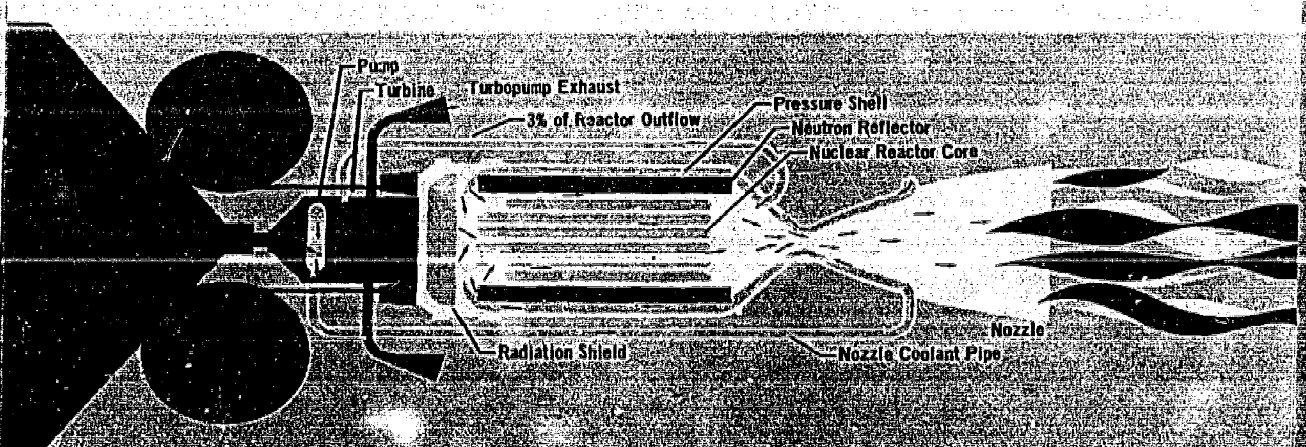


A hemispherical cavity about 75 feet high and 134 to 196 feet across remained from the GNOME explosion. Note man, standing on rubble, right center.

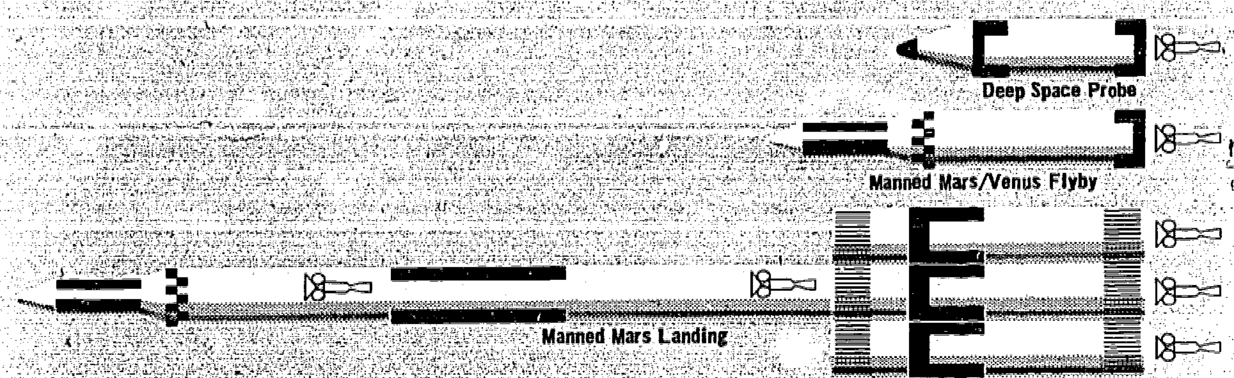
weighs only several thousand pounds, which can be emplaced in a drilled hole only about 1 yard in diameter. Two million pounds of TNT is a gigantic package of several thousand cubic yards that would be difficult and costly to handle and emplace, prohibitively so at a site far underground. The basic cost of the chemical explosive itself would also be many times more than the nuclear explosive.

SPACE EXPLORATION*

Immense amounts of chemical energy must be expended in space travel to propel the vehicle, especially out of the main pull of earth gravity. The first stage of the Saturn-V moon rocket generates as much energy per second as a million automobile engines. The rocket engine and propellant fuel must also be compact and lightweight, before the space vehicle can carry them. For travel within deep space, nuclear energy precisely meets these criteria, more expeditiously than chemical energy, the only alternative. A nuclear reactor supplies the energy for propulsion. A breadboard version of the complete engine system has



Schematic of the NERVA (Nuclear Engine for Rocket Vehicle Application)



Schematic of NERVA engines as part of a basic NERVA propulsion modu'e that can be applied singly or in clusters

already been run at full power for 60 minutes, longer than would be required for most space missions! The difficult technological end goal has been described as a flyable compact reactor, not much bigger than an office desk, that will produce the power of Hoover Dam from a cold start in a matter of minutes. Additional energy in space exploration will be needed to gain and communicate information, and to protect and sustain life, especially for any extended stay away from earth.

Closer to earth, the rebroadcast of television events around the world by means of communication satellites has become fairly routine, as has also the use of satellite aids for navigation and weather reporting. These satellites are usually powered by electricity generated by heat from decaying radicisotopes. Thermocouples convert the radioisotopic heat directly into electricity.†

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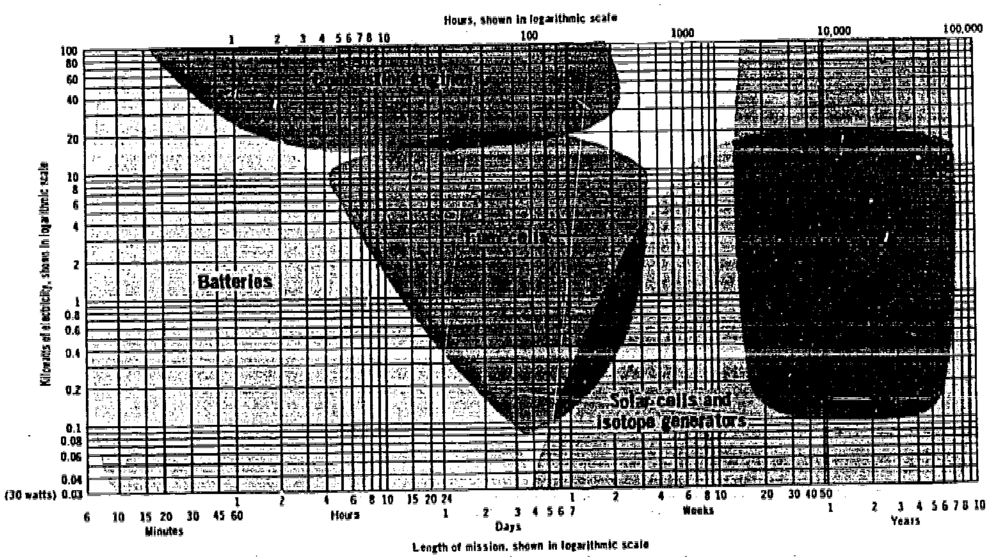
*For more information see *Nuclear Propulsion for Space*, an Understanding the Atom booklet, *Nuclear Propulsion for Rockets*, available from USAEC, and *Nuclear Energy in Space Exploration*, also available from USAEC.

†For more information see Understanding the Atom booklet, *Direct Conversion of Energy*.

Power requirements versus the length of mission stay times away from earth. The nuclear and solar power systems are better for long-lived missions.



Nuclear energy, like heat, chemical, and electrical energy, is one of nature's most fundamental forces, and is as old as matter itself. This energy comes in extremely diverse forms. It varies in intensity from the most concentrated energy source known, as produced by fission, to weak emanations by radioisotopes found naturally within every person's body. Nuclear energy is being and will be applied in many fields and activities.*

*For more information see Understanding the Atom booklets, *SNAP-Nuclear Space Reactors, Whole Body Counters, Neutron Activation Analysis, Animals in Atomic Research, Nuclear Power and Merchant Shipping, Food Preservation by Irradiation, The Atom and the Ocean, Atoms in Agriculture, Radioisotopes in Industry*, and *Nuclear Clocks*.

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